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CHEMICAL BIOLOGICAL CENTER

U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND

ECBC-CR-094

TECHNOLOGY SURVEY FOR ENHANCEMENT OF CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR RESPIRATORY PROTECTION

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February 2008

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20080310043

ABERDEEN PROVING GROUND, MD 21010-5424

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
XX-02-2008

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Mar 2006 - Mar 2007

4. TITLE AND SUBTITLE
Technology Survey for Enhancement of Chemical, Biological, Radiological, and Nuclear Respiratory Protection

5a. CONTRACT NUMBER
SPO700-00-D-3180

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Richardson, Aaron W.; Hofacre, Kent C. (Battelle Memorial Institute); and Gardner, Paul D. (ECBC)

5d. PROJECT NUMBER
BO07PRO100

5e. TASK NUMBER
558

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201-2693
DIR, ECBC, ATTN: AMSRD-ECB-RT-PR, APG, MD 21010-5424

8. PERFORMING ORGANIZATION REPORT NUMBER
ECBC-CR-094

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DIR, ECBC, ATTN: AMSRD-ECB-RT-PR, APG, MD 21010-5424

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
COTR: Paul D. Gardner, AMSRD-ECB-RT-PR, (410) 436-6692

14. ABSTRACT
A technology survey was conducted to identify enhancement technologies that offer the most promise for significant advancements in chemical, biological, radiological, and nuclear individual respiratory protection. The focus was on two enhancement areas: protection and physiology. Novel sealing concepts based on responsive materials were sought that offer potential for performance enhancement. The search for cooling technologies focused on air-management systems (i.e., miniature fans and blowers) and thermoelectric devices. Finally, non-carbon based filtration systems that offer improved protection capabilities were sought.

15. SUBJECT TERMS
Respirator Mask Facial seal Cooling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UL	76	Sandra J. Johnson
					19b. TELEPHONE NUMBER *(include area code)* (410) 436-2914

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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EXECUTIVE SUMMARY

The U.S. Army Edgewood Chemical Biological Center, U.S. Army Research Development and Engineering Command, is investigating emerging technologies that offer the potential for advancement in chemical, biological, radiological, and nuclear individual respiratory protection. The objective of this task was to identify technologies that offer potential improvement in field protection factor performance or reduced physiological burden. From a protection perspective, the two areas of focus were the facial seal and filtration. Novel sealing concepts based on responsive materials that may adjust to facial movements or compensate for improper donning were targeted. For filtration, the potential to integrate photocatalytic oxidation or catalytic oxidation reactors into an individual protection system was assessed. Cooling technologies which were considered in the technology survey included miniature air-management systems (i.e., miniature fans and blowers) and thermoelectric devices.

Responsive materials undergo a reversible change in physical shape in response to an external stimulus such as changes in temperature, pressure, electric current or voltage, light, magnetic field, or pH. The technology survey focused on materials that respond to temperature, pressure, or voltage. Example materials identified include shape memory polymers, temperature activated gels, pressure sensitive materials (i.e., foam, gels, air bladders), electroactive polymers, and shape memory alloys. Three generic seal systems were defined: (1) custom fit, (2) passive, and (3) active. The concept for the custom fit seal system is to integrate a responsive material into the seal that can be "molded" to the macroscopic features of the wearer's face. A passive fit system would provide a custom fit and also have the potential to improve the dynamic fit. The primary technologies considered here were the pressure responsive materials such as gels. An active fit system is differentiated because a leakage sensor is needed to identify the leakage. An integrated microprocessor would then be used to control a responsive material, such as an electroactive polymer, at the mask periphery.

A trade-off analysis was performed to select the most promising concepts/ technologies for further consideration. Criteria used in the analysis included, but were not limited to, fit enhancement, ease of use, environmental operability, and maturity level. The passive seal systems tended to have the highest scores. This can be attributed to three primary factors: (1) no power required, (2) potential to respond to dynamic leakage without the need for a leakage sensor, and (3) maturity of the technology. Of the pressure sensitive materials, the encapsulated gels scored the highest. They were considered more durable than air bladders and foams. In addition, the literature indicated that gel seals dissipated heat better than foam seals and, thus, were expected to be more comfortable. Potential technology sources were identified to consider in future efforts.

The active seal systems tended to score the lowest in the trade-off analysis. This was due to the complexity of the system and uncertainty regarding the leak detection system. A leak detection system would be useful to have in the field to verify fit when the mask is donned. Even if an active seal system is not pursued, it is recommended to further assess the potential to monitor leakage based on contact pressure. A real-time sensor could be used to notify the user to manually adjust the mask because of a poor fit during donning. Technology sources were identified that manufacture or develop tactile pressure sensors. Polymeric tactile pressure sensors is an active area of research with the goal to develop artificial skins for robots.

Thermoelectric devices and miniature blowers and fans were reviewed for cooling applications. The ability of thermoelectric devices to provide a constant cooling rate makes them attractive for personal cooling. However, the primary disadvantage is their inefficiency. The coefficient of performance, defined as the ratio of heat adsorbed to the input power, is generally in the range of 0.3 to 0.7. A thermoelectric cooling assembly generally consists of the thermoelectric module, heat plates or fins, and a fan for air applications. Commercial-off-the-shelf assemblies that offered 20 to 30 Watts of cooling were targeted in the survey. Power requirements and weight limit the application to respirators. However, it is recognized that the off-the-shelf systems are not optimized for the current application. In addition, intermittent operation of the system, either through temperature feedback control or user input, may reduce power requirements. Miniature blowers and fans provide a more feasible approach for cooling based on power requirements. These systems can also be used to generate positive pressure within the mask to minimize leakage.

Open literature regarding photocatalytic and catalytic oxidation was reviewed to assess the feasibility of integration into an individual protection system. The issues tended to outweigh the benefits for both technologies. The power requirements for catalytic oxidation are limiting due to the need to operate at high temperatures. Photocatalytic oxidation provides the more likely application to individual protection based on the modest power requirement. For example, the ultraviolet light source used in the prototype Personal Environmental Protection System consumed only 5 W. However, studies have shown that degradation of the catalyst due to adsorption of by-products is problematic. Although it has been shown that rinsing with water often regenerates the catalyst, this may not be reasonable in the field. Photocatalytic oxidation systems are effective at low level concentrations but performance equivalent to that of a C2A1 canister has not been demonstrated. Both of the technologies require a polishing filter downstream of the reactor to absorb toxic decomposition products.

PREFACE

The work described in this report was authorized under Contract No. SPO700-00-D-3180, Task No. 558, and Project No. BO07PRO100. The work was started in March 2006 and completed in March 2007.

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TECHNOLOGY SURVEY FOR ENHANCEMENT OF CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND NUCLEAR RESPIRATORY PROTECTION

1. INTRODUCTION

1.1 Background

The Edgewood Chemical Biological Center (ECBC), U.S. Army Research Development and Engineering Command, is investigating emerging technologies that offer the potential for advancement in chemical, biological, radiological, and nuclear (CBRN) individual respiratory protection. Key elements identified for improvement in advanced mask concepts include enhanced protection (e.g., improved facial seals and filtration) and reduced thermal burden. Novel sealing technologies are sought to improve protection. In addition, air management systems to improve facial cooling and non-carbon based filtration systems that offer increased capacity or protection are sought. The goal is to identify long-term respiratory protection solutions for military and homeland defense applications.

1.2 Objective

The objective of this task was to identify technologies that offer potential improvement in field protection factor performance or reduced physiological burden of CBRN individual respiratory protection devices.

1.3 Scope

A technology survey was conducted to identify enhancement technologies that offer the most promise for significant advancements in CBRN individual respiratory protection. The focus was on two enhancement areas: protection and physiology. Novel sealing concepts based on responsive materials that offer potential for performance enhancement were sought. The search for cooling technologies focused on air-management systems (i.e., miniature fans and blowers) and thermoelectric devices. Non-carbon based filtration systems that offer improved protection capabilities also were sought. General target performance objectives are provided in Section 2.0 for each of the technology areas. The search strategy is summarized in Section 3.0. The survey results are segregated by technology area (i.e., facial seal, cooling, filtration) and are described in Sections 4.0 through 6.0.

2. REQUIREMENTS

This section summarizes the requirements for each of the technology areas. Within each technology area, a brief overview of current issues is provided prior to definition of the requirements. The Joint Service General Purpose Mask (JSGPM) draft performance specification (2003) was reviewed to identify requirements that may impact performance of the identified technologies. Although the advanced mask systems will be expected to exceed these requirements, they do establish a baseline. These requirements are the basis for the trade-off analysis that is described in Section 4.0.

2.1 Facial Seal

Several studies have been performed to characterize the effect of facial dimensions on respirator fit (Oestenstad, et al., 1990; Han and Choi, 2003; Zhuang et al., 2005), but a clear relationship has not been established due to the variability of facial characteristics. This variability is one reason why a mask that actively seals or conforms to the wearer's face is desirable. Leakage occurs when contact between the respirator sealing surface and the face is lost. Crutchfield et al. (1999) defined two types of leakage: fundamental and transient. Fundamental leakage represents the relationship between the respirator and wearer's face when the respirator is donned and transient leakage is a temporary break in the seal due to movement or shifting of the mask. These leakage sites vary both in time and location during wear due to the head and facial movements of the wearer.

Published studies have assessed the field protection factor of military respirators (Scanlon et al., 2003; Van der Gijp and Steenweg, 2004). Scanlon et al. (2003) observed that only 74% of the test subjects were able to obtain an acceptable fit (defined as fit factor (FF) greater than 2,000) during trials performing operationally relevant tasks. The lowest FFs were measured during tasks that had the greatest facial and head movements and highest breathing rates. Profuse sweating by a particular individual likely resulted in low FFs due to mask slippage. Caretti and Gardner (1999) measured significantly lower FFs following exercise under high temperature and humidity conditions. This was at least partially attributed to shifting of the facepiece due to sweating.

The facial seal must be able to accommodate a wide variety of facial shapes, movements, and face secretions (e.g., oils, sweat) (Wetherell, 2003). The system should not impact the size/profile and weight/bulk of the mask. Extending the mask away from the face may degrade field-of-view, increase dead volume within the mask, and hinder the facial seal due to weight distribution. It should not interfere with compatibility with other systems (e.g., helmets). A sealing system that conforms to the facial characteristics and/or flexes to prevent leakage caused by head movement would likely provide improvement in the measured mask FF. The system should not require input or monitoring by the wearer. It should be able to be donned and sealed to the face within 10 seconds. Systems that do not require power are preferred but powered systems will be considered. A system to monitor and locate in-mask leakage is desired.

The draft JSGPM performance specification requires a 0.88 probability of a FF greater than 1.667, 0.75 probability of a FF greater than 6,667, and a 0.68 probability of a FF greater than 10,000. Grove and Chase (2002) recommended a temporary target improvement of 50% in performance as compared to current requirements. However, it can only be speculated that the selected approaches will improve protection at this stage. Thus, two goals were established that are expected to improve performance: (1) the system is capable of providing a custom fit to the user and (2) the system continuously monitors for transient leakage sites and actively responds to force a seal at these sites. In addition, it is desired that the system reduce discomfort and extend wear-time over current systems.

The masks will be exposed to a wide range of environmental conditions when fielded. These exposures must not adversely affect performance of the sealing system. The draft JSGPM performance specification (2003) requires the system to be functional under operational conditions, which are summarized in Table 1. The performance of the system must not be degraded after storage for 12 weeks under simulated arctic, desert, and tropic conditions. Hot/dry, hot/humid, and cold/dry (basic cold) operational conditions were defined based on MIL-STD-810F (2000).

The system also should not be degraded by other exposures such as salt fog, fungus, rough handling, etc. The effects of these adverse environments were considered a low-priority requirement during the concept development stage.

Table 1. Packaged Storage and Operational Environmental Conditions

Environmental Condition	**Temperature (°C)**	**Relative Humidity (%)**
Desert Storage (packaged)	71±3	<15
Arctic Storage (packaged)	-46±3	<15
Tropic Storage (packaged)	45±3	85±5
Hot/Dry Operational	45±3	<10
Cold/Dry Operational	-21±3	<10
Hot/Humid Operational	36±3	75±5

2.2 Cooling

Several studies have been completed to assess the thermal burden of wearing a respirator (Caretti, 2002; Scanlan and Roberts, 2001; Dubois et al., 1990; Gwosdow et al., 1989; Nielsen et al., 1987; Fox and Dubois, 1993). Caretti (2002) compared the core temperatures of subjects performing exercises while wearing a chemical protective suit with and without a mask in an ambient environment of 35°C. He observed that the protective suit provided the greatest contribution to the thermal load. Scanlan and Roberts (2001) used thermal imaging to assess the thermal strain of a military-type respirator while exercising under an ambient temperature of 30°C. The facial skin temperature increased about 0.5°C in areas in contact with the peripheral seal. Skin temperatures in other regions within the mask were actually cooler relative to the unmasked configuration. The authors attributed this to the flow pattern within the mask and enhanced evaporative cooling. Both studies acknowledged that there is a perceived thermal discomfort caused by mask wear. Dubois et al. (1990) measured skin temperatures of test participants at rest wearing respirators in an ambient temperature of 25°C and concluded that wearers felt uncomfortable when skin temperature exceeded 35°C. This is in agreement with Gwosdow et al. (1989). It is expected that facial cooling would increase wear time and reduce sweating within the mask.

The required cooling load is dependent on several factors including environmental conditions, type of individual protective ensemble, and work rate of the wearer. Metabolic heat production during light work generally ranges from 125 to 325 Watts (W) and during moderate work ranges from 325 to 500 W (NAS, 2003). A cooling rate of 300 W has been shown to reduce heat stress under a variety of environmental conditions and work rates (Masadi)

Assuming that the head represents about 10% of the surface area of the body, the target requirement would be 30 W. Lower cooling rates may be acceptable as the objective is to improve comfort. An active cooling source will require a power supply. In 2003, the National Academy of Sciences published a report assessing the power requirements for future dismounted warriors (NAS, 2003). A power budget of 10 to 12 W was allocated for microclimate cooling in the near term development. The cooling system should have minimal impact on the size, bulk, and profile of the respirator, and cannot degrade respirator fit. It also must be compatible with other equipment such as helmets and it should not interfere with communication (e.g., excessive fan noise). The system must be able to operate over the range of environmental conditions that are listed in Table 1. The potential to provide a heating capability in cold temperatures would also be desirable.

2.3 Filtration

Military canisters generally employ a high-efficiency particulate air (HEPA) filter for protection against particulate hazards and an activated carbon bed to protect against gases and vapors. Activated carbon is a proven technology but does have disadvantages. First, it has limited capacity for a broad range of toxic industrial chemicals (TICs). Second, environmental exposure (e.g., hot/humid) can affect the performance of the carbon leading to conservative change-out schedules. Thus, improved filtration technologies are sought to increase filter capacity, broaden protection against TICs, and reduce environmental degradation.

The filtration system must be portable (i.e., mask mounted, belt mounted, or backpack configuration). All concepts considered required a power source. At a minimum, the new technology must provide an equivalent performance with respect to breathing resistance, aerosol filtration efficiency, and gas life performance as currently fielded systems. High priority TICs based on the draft JSGPM performance specification (2003) include phosgene, hydrogen cyanide, arsine, cyanogen chloride, ammonia, carbon disulfide, ethylene oxide, and formaldehyde. A partial list of requirements is provided in Table 2. The breathing gas temperature should not exceed the highest ambient operational temperature.

Table 2. Summary of Baseline Filter Requirements

Performance Test	Requirement
CK gas life	Ct>40,000 mg-min/m^3 at 50 L/min
AC gas life	Ct>40,000 mg-min/m^3 at 50 L/min
CG gas life	Ct>150,000 mg-min/m^3 at 50 L/min
DMMP gas life	Ct>150,000 mg-min/m^3 at 50 L/min
GB Gas Life	Ct>150,000 mg-min/m^3 at 50 L/min
Inhalation Resistance	<30 mmH2O at 85 L/min
Aerosol Filtration Efficiency	>99.99%

3. SEARCH STRATEGY

A literature search was performed to identify potential enhancement technologies for research in the areas of facial seal, cooling, and filtration. Open literature databases searched included, but were not limited to, MEDLINE, Ei Compendex®, Biosis®, SciSearch®, and PubMed. The keywords used in the searches are listed in Table 3 and the actual search strategies are provided in Appendix A. In addition, the Defense Technical Information Center (DTIC) and Chemical Biological Information Analysis Center (CBIAC) databases were searched to identify technical reports generated for or by the U.S. Department of Defense.

Table 3. Summary of Keywords by Technology Area

Technology Area	Keywords
Facial Seal	(smart or intelligent or responsive) and material, ((polymer or sol or morph) and gel), hydrogel, pressure sensitive, adhesive, mask, respirator, fit, comfort, seal
Cooling	Personal cooling, microclimate, thermoelectric, mask, respirator
Filtration	CATOX, catalytic oxidation, photocatalytic oxidation, microreactor, portable, manportable, battlefield, mask, respirator

A market survey was performed to supplement the literature review and identify commercially available technologies that could be incorporated into a military gas mask to improve protection. Internet searches were performed using keywords similar to those summarized in Table 3. The online ThomasNet® directory (www.thomasnet.com) was used to identify manufacturers of thermoelectric coolers, miniature fans, miniature blowers, and catalytic oxidation systems. To identify novel approaches for sealing a respirator to the face, U.S. and European patent databases were searched using the following keywords: mask, respirator, face, facial, seal, and fit. Relevant companies were contacted by telephone or email to request product literature.

4. FACIAL SEAL ENHANCEMENT

Responsive materials undergo a reversible change in physical shape in response to an external stimulus such as a change in temperature, pressure, electric current or voltage, light, magnetic field, or pH. These responsive materials are also referred to as active, smart, or intelligent materials and find application in a variety of fields including medical (e.g., drug delivery, implants), aerospace, textile, robotics (i.e., artificial muscles), and sensors. The technology survey to enhance the facial seal focused on materials that respond to temperature, pressure, or voltage. The generic technology areas are summarized in Figure 1. Potential materials and face seal concepts are described in Sections 4.1 through 4.5. A trade-off analysis to select the most promising concepts for further consideration is provided in Section 4.6.

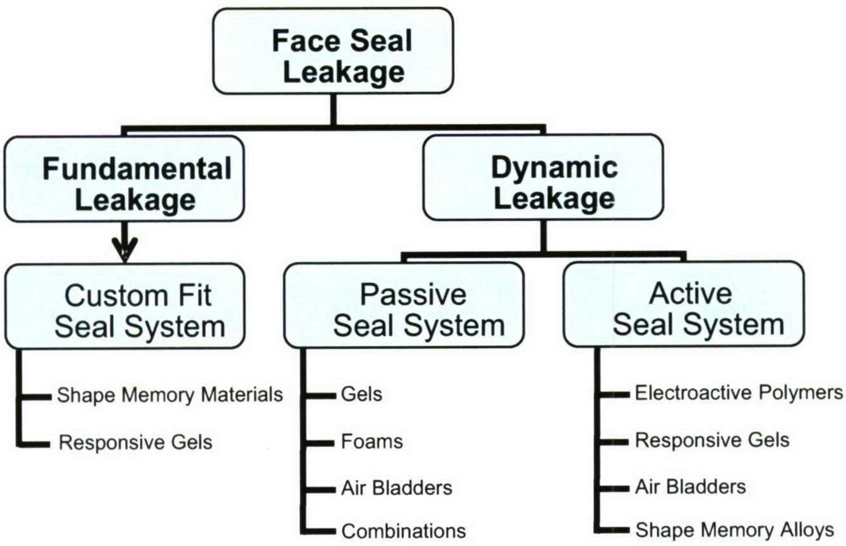

Figure 1. Summary of Concepts to Address Fundamental and Dynamic Leakage

4.1 Custom Fit Seal System

The concept for the custom fit seal system is to integrate a responsive material into the seal that can be "molded" to the macroscopic features of the wearer's face. The technology survey focused on temperature activated polymers and gels.

4.1.1 Shape Memory Materials

Respironics® has patented an approach for providing a custom fit respirator based on a temperature activated material (Scarberry et al., 2005). The Profile™ Lite Nasal Mask is shown in Figure 2. The gel cushion is heated when placed in hot water and then is compressed to the face to shape. The gel has a stiffening agent that retains the shape when cooled. The gel cushion can be fit multiple times by reheating. The sealing surface before and after molding is shown in Figure 3. The gel cushion consists of two layers. The inner layer contains the stiffening agent that provides the customized shape of the face on the macro-scale. Scarberry et al. (2005) report that a satisfactory seal may not result strictly from a customized sealing surface as it will not account for movement or changes in the facial shape. Thus, the outer layer of the seal on the Profile™ Lite Nasal Mask has a soft gel cushion that enhances the seal during movement and accounts for slight variation in facial geometry over time.

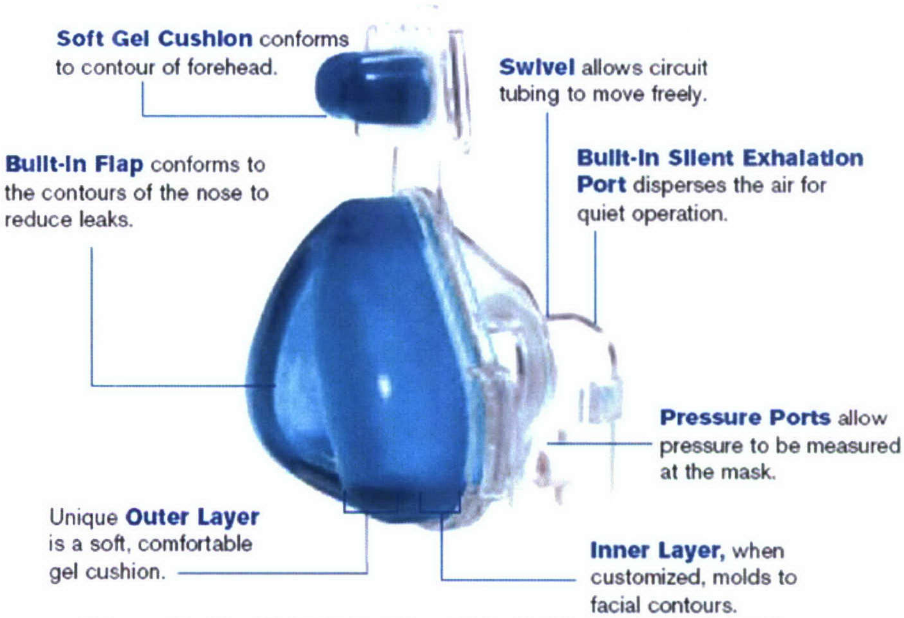

Figure 2. Profile™ Lite Nasal Mask (Respironics, 2007)

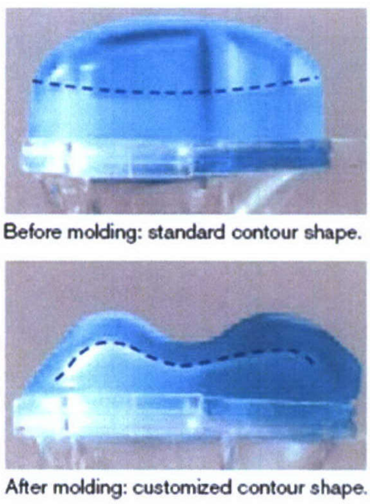

Figure 3. Profile™ Lite Nasal Before and After Custom Molding (Respironics, 2007)

Lang (2004) has patented another concept for a custom fit nasal mask. In Lang's approach, the plastic mask housing is shaped after heating above 120°C. The resulting deformation of the housing shapes the sealing surface. As with the Respironics product, it can be repeatedly fit to different facial shapes.

Several other technologies were identified that provide a custom fit for personal protective equipment or sporting apparel. Aearo Technologies (Indianapolis, IN) markets the Custom E-A-R™ earplug that is custom molded to the ear canal. The plug is positioned in the ear and injected with a soft silicone that expands to take the shape of the ear canal. A similar approach could be envisioned for a respirator seal. The respirator would be donned and the seal would contain a bladder with an injection port for introduction of the silicone or gel. The Sole Slim Sport from Edge Marketing (Great Falls, MT), shown in Figure 4, is a heat moldable foam insert for athletic shoes. The inserts are heated to 90°C and then are form fitted to the wearer's foot. The heat moldable material is variable density ethylene vinyl acetate (EVA) foam. Heat moldable liners are also used to provide custom fit ski boots. For example, Garmont (Williston, VT) manufactures G-fit thermoformable liners that are based on EVA foam. Lawrence Livermore National Laboratory (LLNL) has developed a shape memory foam for medical use to fill and seal cranial aneurysms (LLNL, 2007).

Figure 4. Heat Moldable Athletic Shoe Inserts (Sole, 2007)

Shape memory polymers exist in two states: permanent and temporary. The permanent shape can be deformed by applying an external stress at or above the transition temperature, which is also referred to as the glass transition temperature. This temporary shape is maintained when the material is cooled below the transition temperature. The permanent shape can be regained by heating the material above the transition temperature. Shape memory polymers tend to soften when heated and harden when cooled, as illustrated in Figure 5. The elastic modulus of shape memory polymers is generally 800 MPa in the permanent state and only about 2 MPa in the rubbery state (Wei et al., 1998). The primary disadvantage of shape memory polymers from a respirator seal perspective is their rigidity under ambient temperatures. However, they could be coupled with a gel or foam to provide sealing on the micro-scale.

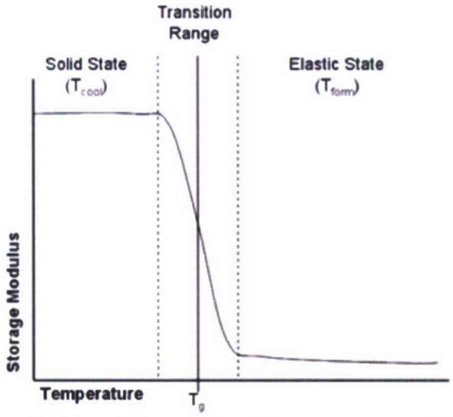

Figure 5. Illustration of Glass Transition Temperature (CRG Industries, 2007)

Cornerstone Research Group (CRG) Inc. (Dayton, OH) manufactures a range of shape memory polymers and has a significant research and development capability. Products developed for commercialization are sold through CRG Industries (Dayton, OH). Two materials of potential interest are Veriflex®, shown in Figure 6, and Verilyte®, a shape memory foam. Veriflex® is a two-part thermoset that goes from rigid to elastic when its temperature is increased. The physical properties and activation temperature can be adjusted. The standard activation temperature is 62°C. Verilyte is a shape memory foam that exists in a rigid and pliable state. It has a customizable activation temperature and can expand by up to 400%.

Figure 6. Veriflex® Shape Memory Polymer from CRG Industries (CRG Industries, 2007)

The Polymer Technology Group (Berkeley, CA) manufactures a shape memory thermoplastic referred to as Calo•MER. Calo•MER can be produced with any transition temperature between -40 and 70°C, to a tolerance of ± 2°C. The hardness of the material at the transition temperature can be varied. The material was developed for medical applications. Landec Intelligent Materials (Menlo Park, CA) manufactures a range of products for food packaging and cosmetic/personal care applications. They produce Intelimer® polymers, which are thermally activated materials with customizable physical properties such as permeability, adhesion, or viscosity. The activation temperature can be customized between 0 and 70°C and the polymers respond over a very sharp temperature range (+/-1°C). The Intelimer® polymer is the basis for their seed coating, Intelicoat, which is a temperature-activated coating that regulates adsorption of water by the seeds. Landec also produces a temperature-responsive skin-contact adhesive that loses it adhesive properties when heated, thus, providing pain-free removal from the skin.

4.1.2 Responsive Gels

Responsive gels undergo a volume or phase change in response to temperature changes. For example, hydrogels can absorb large amounts of water and can swell up to 1,000 times their original volume (Wei et al., 1998). They are used in implants, diapers, contact lenses, artificial muscles, drug delivery devices, and wound care. The most common temperature responsive hydrogels are poly(N-isopropyl acrylamide) (NIPA) and polyvinyl alcohol (PVA) (Hassan and Peppas, 2000). For medical applications, the transition temperature is tuned to body temperature (37°C) so that an implant can be placed into the body through a small incision and then can expand upon reaching body temperature. Li et al. (1996) synthesized gels that can change shape in response to temperature. These "modulated" gels consist of two gels: one that expands or contracts in response to the environmental stimulus and one that does not. This results in a bending motion.

In general, the rate of contraction or expansion of gels is limited by the transport of water in or out of the polymer matrix. For artificial muscle applications, bundles of micro-sized gel fibers are typically bound together to provide a rapid response. Studies have also been performed to increase the response rate by controlling the porous structure of the matrix (Zhang and Zhou, 1999; Van Durme et al., 2005).

Mide (Medford, MA) is a research and development company that specializes in shape memory materials including alloys, hydrogels, and electroactive polymers. Mide has developed products based on hydrogels for the U.S. Navy, including a wetsuit that provides heat regulation and a shaft sealing system for ships. The SmartSkin™ wetsuit adjusts the permeability of the fabric based on thermal conditions by expanding or contracting.

BioSyntech develops thermogels for a range of medical applications. They produce a gel, referred to as BST-Gel®, which is a liquid at low temperature and a solid at body temperature (37°C). The BST-Gel® is intended to be injected into the body to repair damaged tissue or bones.

Foster-Miller (Waltham, MA) develops advanced materials for a range of applications and has expertise in coatings, gels, polymers, and ceramic composites. One product of specific interest is Morph™ gel (see Figure 7) that changes from a semi-liquid state to a firm gel in response to an increase in temperature. The semi-liquid state readily conforms to the contours of the body. This shape is then retained as the gel temperature reaches body temperature and the viscosity of the gel increases. The transition temperature and hardness of the gel can be tailored to the specific application. This material has been used in sleep apnea masks to provide a custom fit (Nighswonger, 2002). A disadvantage of the Morph™ gel is that it returns to the liquid state when the temperature decreases. Thus, it does not have any shape memory properties.

Figure 7. Morph™ Gel from Foster-Miller (2007)

4.2 Passive Seal System

A passive seal system is based on a pressure responsive material that conforms to the face. The material expands or contracts in response to changes in contact pressure between the face and sealing surface. Although it provides a custom fit, it is differentiated from the custom fit seal system described above because of the potential to also respond to dynamic leakage. The technology survey focused on encapsulated gels, air bladders, foams, and combinations.

There have been a considerable number of studies performed to characterize the ability of these types of materials to improve the facial seal. Stark et al. (1988) assessed a variety of concepts to improve the protection factor of the M40 including one that placed a foam pressure pad between the in-turned lip and facepiece (refer to Figure 8) and added a foam pad between the temple strap and facepiece (refer to Figure 8). The foam inserts were to provide additional pressure at the sealing surface. Prototypes of each concept were prepared for human subject protection factor testing. The foam inserts did not increase protection, but unexpectedly resulted in a reduction in the protection factor. Details regarding the type of foam used were not provided. The concept was eliminated from further consideration.

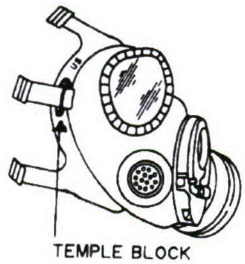

Figure 8. Location of Foam Inserts Integrated into Mask Prototypes (Stark et al., 1988)

Battelle (1990) generated concepts to improve the facial seal as part of the RESPO 21 program. Design requirements included a seal that conformed to the face, had a low profile, improved comfort, and allowed for seal replacement (not integral part to mask). Technologies considered included pneumatic air bladders, encapsulated gels, laminated foams, and combinations of these technologies. Specific technologies included a biosoft gel bicycle seat cover made by Spenco, gel/foam headphone ear cushions from Bose, an air bladder from an athletic shoe, and a slow recovery foam. A prototype system with a pneumatic bladder was completed, but no testing was performed to assess the design.

Grove and Tardiff (1992) provide an overview of the advantages and disadvantages of various sealing approaches. Mechanisms reviewed various seal designs including flat, ribbed, in-turned lip, bladder (foam, gel, air), mechanical, and neck sealing. The authors speculate that encapsulated gel seals may provide greater protection factors than in-turned lip designs.

Several commercially available sleep apnea masks use an air bladder, foam, encapsulated gel, or a combination. A proper seal that is comfortable to the patient is important for this application to ensure that the pressurized air is delivered to the wearer. Some example masks are summarized in Table 4. These companies represent potential technology sources for pressure sensitive seals. Several patents were identified in the literature search and are summarized in Appendix B.

Table 4. Summary of Sleep Apnea Masks that Contain Pressure Sensitive Seals

Company	Product	Technology
Respironics	Comfort Gel	Encapsulated gel
Sleepnet	Mojo	Encapsulated gel
Hans Rudolph	Ultimate Seal	Encapsulated gel
Respironics	Total	Air bladder
Resmed	Mirage Activa	Air bladder
Sunrise Medical	FlexAire	Air bladder
Hans Rudolph	Comfort Seal	Foam
Fisher Paykel	FlexiFit	Foam

Scarberry et al. (1999) recommend gel over foam seals because they dissipate heat better and, thus, are more comfortable. Two examples of sleep apnea masks that contain encapsulated gels are the Mojo Sleepmask (Sleepnet, Manchester, NH) and the Comfort Gel mask from Respironics. Scarberry et al. (1999) recommend using a gel that has similar recoil as the soft tissue in contact with the respirator such as a polyurethane with a durometer of 20 to 45 on a Shore 00 scale.

Several companies produce gels or apply them in commercial products. For example, Gel Smart (Whippany, NJ) manufactures a range of products for personal care applications. The company offers a product development capability and has expertise in silicone gels and thermoplastic elastomer (TPE) gels. Gel Smart's TPE gels include both M-GEL medical-grade, mineral-oil based soft-gel materials and T-GEL(TM) higher-durometer oil-based gels. Mentor produces Memory Gel for breast implants. ILC Dover is developing a self-repairing space suit that incorporates a pressure sensitive gel (Shiga, 2006). The polymer gel is contained between two layers of polyurethane. If the space suit is damaged by debris, the fluid gel acts to seal the hole. It can fill holes up to 2 mm in diameter. Bose uses proprietary technology, referred to as QuietComfort® ear cushions, to seal noise-cancelling head phones to the wearer. These ear cushions have a compliant elastomeric gel encapsulated in a thin, pliable membrane. The gel is backed with a layer of slow recovery foam which provides mechanical support (Battelle, 1990). The Bose ear cushion conforms to the irregular surface of the human head surrounding the ear. An adequate seal is important to prevent acoustical transmission. Bose produces the Combat Vehicle Crewman Headset for military applications that also contains the seal technology. Foster-Miller also indicated experience in developing encapsulated gels (Grove, 2007).

Several patents were identified for continuous positive airway pressure (CPAP) masks that incorporate air bladder seals (Toffolon, 1990; Sullivan and Bruderer, 1993; U.S. Patent Nos. 4,971,051, 5,243,971, 7,044,130, 6,418,928, and 57,38,094). The masks generally contain membranes that are inflated using the supply pressure. An example is the Total full-face mask shown in Figure 9. Wetherell (2003) noted that airbag seals provide very good protection when incorporated into an APR and are comfortable. However, they are expensive to manufacture as they have to be molded separately from the faceblank. Air bladders also have durability issues. The skin of the airbag must be thin to permit conformance to the face. Gambone et al. (2004) indicate that 25-30% of CPAP masks with air bladders cannot be used due to leaks. They recommend foam seals as they provide improved durability.

A patent application was identified from Safety Tech International (Frederick, MD) that described a pneumatic system for sealing air-purifying respirators (Gosweiller, 2005). The mask has a double diaphragm pump that inflates the air bladder seal. During inhalation, the space between the diaphragms fills with filtered air. The trapped air is then forced into the bladder during exhalation. A patent application from Morning Pride Manufacturing (Dayton, OH) described an inflatable bladder used to seal a protective hood to a face mask (Grilliot and Grilliot, 2005). The design used positive pressure from a supplied air source or cylinder to pressurize the seal.

Figure 9. Total Face Mask from Respironics (Respironics, 2007)

4.3 Active Seal Systems

Active seal systems would detect leakage into the mask and respond to seal the leak. The system would consist of three primary components: (1) leakage sensor, (2) control system, and (3) responsive material at the facial seal. This approach is considered a long-term solution as the technologies require further development. The technology survey focused on electroactive polymers (EAPs), temperature activated gels/polymers, and shape memory alloys. In addition, a brief survey was completed to identify potential technologies that could be utilized as a leakage sensor.

4.3.1 Electroactive Polymers

Electroactive polymers (EAPs) can be induced to stretch, bend, or contract by applying a voltage. EAPs are being developed for application in actuators, miniature pumps, vibration sensors, and artificial muscles. Bar-Cohen (2005) indicates that EAP-based actuators are not robust and exhibit low efficiency which limits their practical application. Thus, EAPs should be considered a high-risk, long-term solution as further fundamental research is needed prior to application. There are two classes of EAPs, ionic and electric, that differ based on their activation mechanism. Electric EAPs are driven by electrical fields while ionic EAPs are driven by movement of ions. Table 5 compares the general characteristics of each class and provides their associated advantages and disadvantages.

Table 5. Comparison of Ionic and Dielectric EAPs (Bar-Cohen, 2001)

EAP type	Advantages	Disadvantages
Electronic EAP	• Can operate in room conditions for a long time • Rapid response (mSec levels) • Can hold strain under DC activation • Induces relatively large actuation forces	• Requires high voltages (~150 MV/m) • Requires compromise between strain and stress • Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	• Large bending displacements • Provides mostly bending actuation (longitudinal mechanisms can be constructed) • Requires low voltage	• Except for CPs, ionic EAPs do not hold strain under DC voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • Except for CPs, it is difficult to produce a consistent material (particularly IPMC) • In aqueous systems the material sustains hydrolysis at >1.23-V

Dielectric elastomers are an example of an electric EAP. Polyurethanes and silicones are two materials that undergo large displacement when electroactivated (Bar-Cohen et al., 1998). The elastomer is positioned between two electrodes and a voltage is applied causing the change in shape. The elastomer contracts between the electrodes and expands perpendicularly. The electrodes are generally a thin, flexible coating. They are most widely used due to their fast electromechanical response and high generative forces (Harrison and Ounaies, 2001). However, electric EAPs require higher voltages than ionic EAPs which can make them unsafe in many applications (Ramaratnam and Jalili, 2006). Thin films of dielectric material are used to reduce the required voltage. The dielectric material will hold an induced displacement when a voltage is applied. SRI International (Menlo Park, CA) has developed dielectric EAPs for application in micromachines and power generation. Artificial Muscle (Menlo Park, CA), a spin-off of SRI International, markets and develops the dielectric elastomers. The Universal Muscle Actuator is a linear actuator that makes a piston-like motion and has potential application as a valve or pump. It has a 50 mm diaphragm that can undergo 10 to 15% strain. A single layer of material provides 0.6 N of force. The force increases linearly with each additional layer. The system is designed to operate on 1.5 to 12 V. Artificial Muscle has two divisions being materials development and device development. Artificial Muscle maintains a relationship with SRI International.

In comparison, ionic EAPs respond to low voltages (generally 1 to 5 V) but require a wet media as they operate in the presence of electrolytes. There are two primary types, being ionic polymer gels and ionic polymer metal composites. The polymer gels swell or contract while the ionic polymer metal composites undergo a bending motion. Both are driven by the diffusion of ions. Ionic EAPs are advantageous because of their low voltage; they have large displacements, but tend to respond slower than electric EAPs as they are diffusion rate limiting. In addition, the need to keep the polymer or gel wet has limited the commercial application of ionic EAPs (Ramaratnam and Jalili, 2006). Flexible coatings are being developed for ionic polymer metal composites to remove this limitation.

Environmental Robots, Inc. (ERI, Albuquerque, NM) develops and manufactures ionic EAPs. An example product, the Bending/Flexing Artificial Muscle Kit, is shown in Figure 10. It is able to operate in ambient air if there is sufficient humidity. The actuation voltage is about 10 V/mm thick. The tip movement is a function of the thickness. Increasing the thickness reduces the range of tip movement but permits exertion of larger forces. ERI also manufactures ionic polymers marketed for artificial muscle applications.

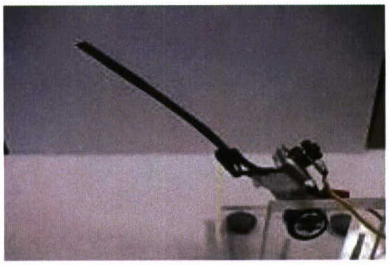 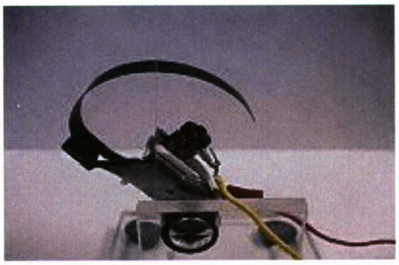

Figure 10. Bending Motion of Ionic Polymer Metal Composite EAP (ERI, 2007)

Micromuscle AB (Linkoping, Sweden) is developing ionic gels that swell and contract when a voltage is applied. Swelling is caused by ions and water entering the polymer. When the voltage is removed or reversed, the polymer contracts and resumes its original shape. The gels are very thin (<200 μm) but undergo 20-30% expansion and operate on only 1-2 V. The gels are being developed for surgical devices and must be in an aqueous solution to operate. The Nondestructive Evaluation and Advanced Actuators Technologies laboratory at the Jet Propulsion Laboratory performs research to characterize EAP materials. The laboratory does not perform any materials development. It is strictly application driven with a goal to develop miniature, low weight, low power actuators.

4.3.2 Temperature Activated Polymers/Gels

Temperature activated materials were discussed in Section 4.2.1. For application as an active seal system, resistive heaters would be imbedded in the facial seal. The responsive polymer or gel would bend or swell upon heating to force compliance of the sealing surface to the face.

4.3.3 Pressure Sensitive Materials

The concept is to design a mask seal consisting of a thin continuous air bladder, or incorporating separate air bladders under critical sealing areas of the mask such as the chin, cheek, and/or temple regions. A miniature electronic pump or hand pump would be used to pressurize the air bladders. A pressure-sensing device would be used to regulate inflation of the air bladders by constantly monitoring skin contact or bladder pressure. Air bladder technologies were described in Section 4.2.

4.3.4 Shape Memory Alloys

Shape memory alloys are metals that change shape upon heating. Example shape memory alloys include copper-zinc-aluminum, copper-aluminum-nickel, and nickel-titanium, referred to as Nitinol. Nitinol is the most commonly used due to its favorable mechanical properties (Machado and Savi, 2003). In general, a temperature change of only about 10°C is necessary to initiate the shape change. The elemental ratios can be varied to adjust the transition temperature. There are two general types of shape memory alloys, being one-way and two-way shape memory. In one-way shape memory, a mechanical force is required to deform the alloy at the low temperature conditions. Upon heating above the transition temperature, the alloy will return to the original shape and the deformed shape forgotten. Thus, when cooled, it will retain the original shape. In contrast, in a two-way shape memory alloy, the alloy returns to the deformed shape when cooled. An applied force is not required to reshape the alloy upon cooling. From this perspective, a two-way shape memory alloy would be required for the current face seal application.

Shape memory alloys are used as actuators, artificial muscles, metal seals, and medical applications including surgical instruments and implants (Machado and Savi, 2003). An example of medical use is self-expanding stents to maintain the inner diameter of weakened blood vessels. The stent is inserted into the blood vessel in the deformed state and expands to maintain the diameter of the vessel upon reaching body temperature. Shape memory alloys are also being used as actuators and artificial muscles in miniature robotics. Flexinol is an example of a commercially available alloy sold for this purpose.

Studies have been performed to characterize the behavior of shape memory alloys integrated into polymers (Murasawa et al., 2004; de Blonk and Lagoudas, 1998; Barrett and Gross, 1996). The shape memory alloys are generally heated by electric current. Blonk and Lagoudas (1998) integrated Nitinol wires into an elastomeric rod and used resistive heating to actuate the wires and induce bending. Deflections of up to 11.5 mm were observed in the silicone elastomeric rod. Similarly, Barrett and Gross (1996) integrated Tinel alloy K wires into a 0.25 cm thick, 25 durometer silicone matrix, as shown in Figure 11, with the goal of developing an artificial muscle. Silicone was selected as it is biologically inert. Resistive heating was used to actuate the alloy wires that changed shape to expand or contract the silicone slab. The test slabs were approximately 5 cm in length and the radius of curvature shown in Figure 11 is approximately 1.2 cm.

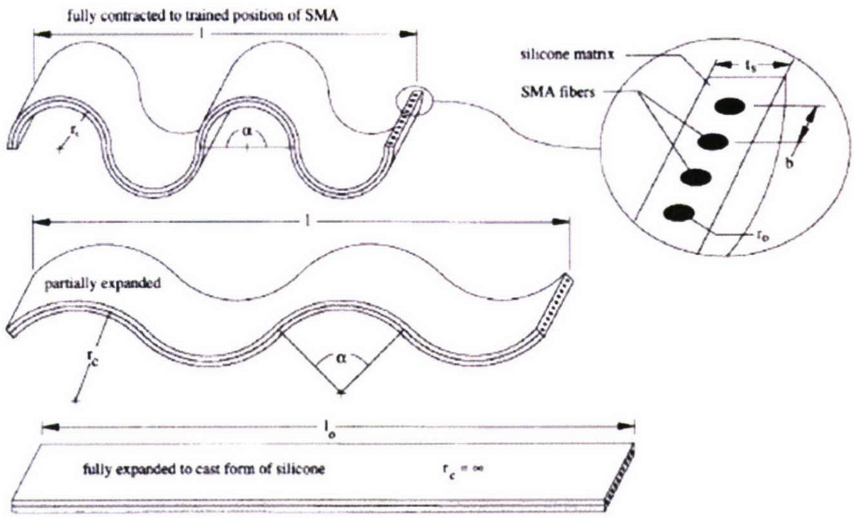

Figure 11. Shape Memory Alloy Composite (Barret and Gross, 1996)

Potential technology suppliers include Mide Technology Corp. (Medford, MA), Dynalloy, Inc. (Costa Mesa, CA), Memry Corp. (Bethel, CT), and TiNi Alloy Company (San Leandro, CA). These companies have developmental capability geared toward medical or aerospace applications. Of particular interest is Mide as they also have expertise regarding temperature activated gels as described in Section 4.1.2. Dynalloy manufactures Flexinol which is commonly used as an actuator. The wires contract 2 to 5% of their length when heated. Wire diameters range from 0.001 to 0.02 inches and contract within one second. The Center for Intelligent Material Systems and Structures at Virginia Tech also has expertise in shape memory alloys.

4.3.5 Leakage Sensors

An important aspect of an active system is the need for a leakage sensor. Ideally, the sensor would be integrated around the facial seal to permit identification of the leak location. This information would then be used to control a localized response to seal the leak. Potentially the system could be simplified by focusing on trouble spots for sealing such as the temple region. Two general approaches were considered for the sensor based on measurement of either contact pressure or a chemical target.

4.3.5.1 Contact Pressure

Cohen (1999) measured the contact pressure between a M40 mask and headform as a function of strap tension. Tactile pressure sensors were inserted between the mask sealing surface and headform. An example result is shown in Figure 12 that illustrates the contact area around the seal. The contact pressure in the temple/forehead regions was generally higher than that measured in the cheek region. The largest differences in contact pressures between trials with good and poor fits were observed in the temple and forehead region. The authors recommended further evaluation of methods to measure contact pressure to assess mask fit.

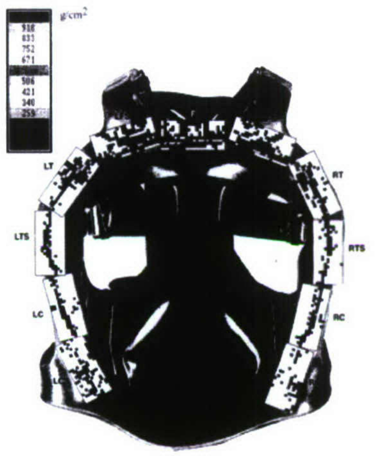

Figure 12. Seal Pressure Distribution as Measured by Cohen (1999)

Development of tactile pressure sensor films is currently an active area of research with a goal to develop sensors that mimic human skin for robotic applications (Someya et al., 2004; Engel et al., 2005; Kim et al, 2004; Stiehl et al., 2004). Researchers at the Micro Nano Technology Research Group at the University of Illinois are developing tactile pressure sensors based on microelectromechanical systems (MEMS). The sensors are fabricated from polymer materials and metal thin film sensors and are designed to detect hardness, thermal conductivity, temperature, and surface contours (Engel et al, 2005). The research group is also developing artificial haircells for sensing flow and vibration (Yang et al., 2006; Tucker et al., 2006). The flow is measured based on the deflection of the haircell. An example haircell is shown in Figure 13.

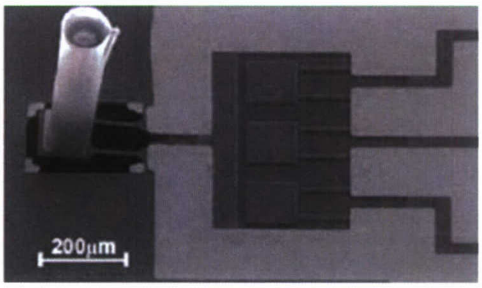

Figure 13. Artificial Haircell for Flow Measurement (Yang et al., 2006)

Tekscan, Inc. (South Boston, MA) manufactures flexible tactile array sensors that are about 0.1 mm thick that are used for measuring pressures ranging from 0 to 15 kPa. They have a range of commercial products for assessing seat cushions for seating, foot care products, wind shield wipers, and gasket seals. The sensors are available in custom shapes. The spatial resolution of the sensors can also be customized with up to 170 sensing locations being integrated into a 1 cm^2 area.

Sensor Products Inc. (SPI, Madison, NJ) produces a range of tactile pressure sensors for assessing sealing surfaces. Commercial products are available that provide a qualitative indication of pressure based on a colorimetric response. Quantitative sensors are also available. Point pressure transducers used with the Tactilus system have diameters ranging from 2 to 12 mm with thicknesses as low as 0.25 mm. Up to 32 of them can be used simultaneously to monitor pressure at different points. Alternatively, an “electronic” skin can be used. An example of a product to evaluate squeegees is shown in Figure 14. The sensing area is 1 x 80 cm and contains up to 800 sensors. The thickness is 0.4 mm. It is envisioned that such a sensing skin could be integrated into the facial seal.

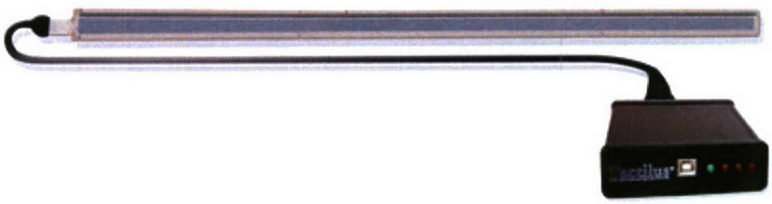

Figure 14. Pressure Sensor Array from SPI (SPI, 2007)

Tactex Controls, Inc. (Victoria, British Columbia) manufactures Kinotex®, a tactile force sensor that is unique due to its measurement method. It is a foam that contains “transmit” and “receive” fibers. A light is shown through the transmit fibers and the light intensity returned in the receive fibers is measured. The compression of the foam, and hence the amount of light measured in the receive fiber, is a function of the applied force.

4.3.5.2 Chemical Target

SeaCoast Science, Inc. (Carlsbad, CA) develops MEMS-based sensors for detection of volatile organic compounds, chemical warfare agent, and toxic industrial chemicals (TICs). SeaCoast Science reports on their website that sensitivities in the parts per million range have been demonstrated for several compounds. The small size of the sensor units is demonstrated in Figure 15. The SC-210 Modular Chemical Detection System that also contains the needed electronics and power supply weighs less than 100 g. One problem associated with the use of a chemical detection approach to monitor leakage is the selection of the target chemical. The challenge agent will likely be unknown during a typical operation. Another problem is the integration of the sensors into the facial seal to provide sufficient resolution to identify leak location.

Figure 15. SeaCoast Science Sensor Technology (SeaCoast, 2007)

4.4 Other Potential Seal Enhancement Technologies

Two masks in the market that use a hypoallergenic adhesive to form the facial seal were identified. Neither mask has a harness. Both are intended for protection against biological aerosols, either during escape from a terrorist attack or protection during a flu pandemic. The ViraMask™, developed by Wein Products, Inc. (Los Angeles, CA), seals around the nose and mouth. The Survival Mask from EvacuTech (Brooklyn, NY) protects the eyes, nose, and mouth. These approaches were not considered viable for the current application due to durability and contamination concerns. The products described above are designed for escape and, thus, intended for one-time use. Contamination of the adhesive during non-wear could hinder a mask's seal.

Dry adhesives provide another opportunity. Research groups at Carnegie Mellon, University of Akron, and University California-Berkeley are developing bio-inspired adhesives based on the gecko lizard. A gecko's foot is covered with tiny hairs that branch into nanoscale tips. The dry adhesion forces are due to Van der Waals forces. Researchers at the University of Akron are developing gecko adhesives from carbon nanotubes that have adhesion forces 200 times higher than those observed with gecko foot-hairs (University of Akron website, 2005). Gorb et al. (2007) have developed a similar adhesive based on the beetle that contains mushroom-shaped adhesive microstructures. The study indicates that the dry adhesive can be washed in a soap solution and still retain its adhesive properties.

The Intelligent Polymers Research Group at Wollongong University in Australia has developed a fiber with a coating that has the ability to expand or contract (ABC Science online, 2000). The contraction and expansion of the fibers are controlled using a microprocessor. The fibers have been integrated into a "smart bra" that controls strap tension. A similar concept could be applied to a respirator harness.

4.5 Summary

In summary, a market survey was performed to identify potential technologies that could be used to enhance the respirator facial seal. Table 6 lists the companies and research organizations that have products or expertise relevant to responsive materials that were identified in the survey. The generic facial seal concepts based on the responsive materials are summarized below. The concepts have been divided by seal type.

Table 6. Summary of Companies Identified in Technology Survey

Company	Seal Type	Technology
Respironics	Custom/Passive	Shape memory gel/gels/air bladders
CRG	Custom	Shape memory polymers
Polymer Tech Group	Custom	Shape memory polymers
Landec	Custom	Shape memory polymers/temperature activated coatings
Mide	Custom/Active	Responsive gels/shape memory alloys
Biosyntech	Custom	Responsive gels
Foster-Miller	Custom	Responsive gels/encapsulated gels
LLNL	Custom	Shape memory foam
Resmed	Passive	Gel seal
Hans Rudolph	Passive	Gel Seal/Foam
Sunrise Medical	Passive	Air bladder
Sleepnet	Passive	Gel seal
ILC Dover	Passive	Gel seal
Bose	Passive	Gel seal
Gel Smart	Passive	Gel seal
Carnegie Mellon	Passive	Dry adhesive
SRI International	Active	EAP
Artificial Muscle	Active	EAP
Micromuscle AB	Active	EAP
Environmental Robots	Active	EAP
JPL	Active	EAP
Dynalloy	Active	Shape memory alloy
Memry Corp	Active	Shape memory alloy
TiNi Alloy Company	Active	Shape memory alloy
Virginia Tech	Active	EAP/Shape memory alloy
University of Illinois	Active	MEMS-based tactile/flow sensors
Tekscan	Active	Tactile pressure sensor
SPI	Active	Tactile pressure sensor
TacTex Controls	Active	Tactile pressure sensor
Seacoast Sciences	Active	Chemical sensor
Wollogong University	Active	Intelligent fibers

4.5.1 Custom Fit Systems

Custom-fit technologies would integrate a responsive material that molds to the macroscopic features of the wearer's face. The market survey focused on temperature-activated materials. The concepts are described below:

- Heat Sensitive Material (Facial Temperature Activation) – Incorporate a temperature responsive gel that is activated at nominal skin temperature that would conform to the face after donning. An example of this technology is the medical mask that incorporates the MorphGel from Foster-Miller or an expanding hydrogel from Mide.

- Heat Sensitive Material (High Temperature Fit) – Incorporate a temperature responsive gel or foam that is activated at a temperature higher than expected during operational wear. In this approach, the seal would be heated above the transition temperature and custom "molded" to the face. Alternatively a heat gun could be used to heat the material after donning. An example of this technology is the Nasal Lite mask from Respironics or the shape memory foam inserts.

- Heat Sensitive Material/Gel Composite – Same approach as described above but combine with a pressure sensitive material to allow response to dynamic leakage. The Nasal Lite mask from Respironics is the only example of this technology identified in the market survey.

- Incorporate a soft metal wire into the seal that can be press fit to conform to face after donning and retains shape.

4.5.2 Passive Seal System

The passive seal system would contain a pressure responsive material that expands or contracts with changes in the contact pressure between the respirator and face. This would provide a custom fit and potentially seal leaks caused by head movement. Masks containing pressure sensitive materials are commonly used in sleep apnea masks. Manufacturers such as Respironics, Hans Rudolph, and Resmed are technology sources. Potential approaches considered include encapsulated gel or liquid, foam, foam/gel combination, air bladder, and dry adhesives.

4.5.3 Active Seal System

Active seal systems would include a sensor to detect leakage into the mask. A microprocessor would be used to control the responsive material at the facial interface. The concepts are described below:

- EAP with Feedback Control - Electroactive polymers can be made to swell or flex when a voltage is applied. An example technology is that being developed by Artificial Muscle for application in micro machines.

- Air Bladder with Feedback Control - A thin continuous air bladder or separate air bladders under critical sealing areas of the mask such as the chin, cheek, and/or temple regions. A miniature electronic pump would be used to pressurize the air bladders.

- Heat Sensitive Material with Feedback Control - Temperature responsive polymer, gel, or shape memory alloy incorporated into the peripheral seal that is equipped with heating elements. The responsive material would be heated to expand or bend to force compliance with the face at the leak location.

4.6 Trade-off Analysis

This section describes the trade-off analysis completed to compare the various technologies and to select the most promising for further consideration. The selection criteria is provided in Section 4.6.1. Results and recommendations are provided in Section 4.6.2.

4.6.1 Evaluation Criteria

The categories considered most important to evaluate the facial seal technologies are summarized in Table 7. A weight factor was assigned to each category based on its relative importance. The heaviest weight factors were assigned to those considered most significant and included: fit enhancement, ease of use, environmental operability, and maturity level. The scoring rationale within each category is also provided in Table 7. Scoring within each category ranged from 1 to 10 except for the unique factors. The unique factors category captured the additional benefits and/or problems that were not accounted for otherwise. A score of plus 5 was given for positive attributes and minus 5 for negative attributes.

Table 7. Facial Seal Technology Evaluation and Scoring Criteria

Category	**Weight Factor (%)**	**Scoring Criteria**
Fit Enhancement	20	10 = Active response to leakage
		5 = Custom fit only
Ease of Use	10	10 = Donning procedure no different than current practice
		5 = User action required only during donning
		1 = System must be continuously monitored by user
Maturity Level	10	10 = Commercially available CBRN mask or prototype
		8 = Commercially available medical mask or prototype
		5 = Technology mature but has not been applied to mask
		1 = Significant developments needed before applying technology
Environmental Operability	10	10 =Unaffected by temperature and relative humidity extremes
		5 = Functions over moderate temperatures but potential to degrade under temperature or humidity extremes
		1 = Will not function properly in extreme temperatures or humidity
Physical Durability	5	10 = Ruggedness of technology demonstrated or expected
		5 = Further research required to assess
		1 = Significant degradation expected
Size/Weight	5	10 = Can be integrated into current mask designs with minimal impact on mask profile
		5 = Technology requires auxiliary equipment (e.g., battery pack, pump) or significant redesign to mask
Relative Cost	5	10 = Low
		5 = Moderate
		1 = High
Power Requirement	5	10 = No power required
		1 = Power required
Logistical Support	5	10 = Requires no replacement parts; only routine maintenance
		5 = Requires replacement parts; only routine maintenance
		1 = Requires replacement parts; calibration prior to each use
Unique Factors	10	5 = Desirable feature not assessed by above criteria
		0 = No features that provide additional benefits
		-5 = Undesirable feature not assessed by above criteria

4.6.2 Results

The results of the trade-off analysis are provided in Table 8. The passive seal systems tended to have the highest scores. This can be attributed to 3 primary factors: (1) no power required, (2) potential to respond to dynamic leakage without the need for a leakage sensor, and (3) maturity of the technology. Of the pressure sensitive materials, the encapsulated gels scored the highest. They were considered more durable than air bladders and foams. In addition, the literature indicated that gel seals dissipated heat better than foam seals and, thus, were more comfortable.

Table 8. Scoring and Ranking of Facial Seal Technologies

Technology	Fit Enhancement	Ease of Use	Maturity Level	Environmental	Physical Durability	Size/Weight	Cost	Logistical Support	Power Requirement	Unique Factors	Raw Score	Weighted Score
Encapsulated Gel	10	10	8	5	5	10	10	10	10	5(a)	83	7.9
Heat Sensitive Material/Gel Composite	10	5	8	5	5	10	10	10	10	5(b)	83	7.65
Foam/Gel Combination	10	10	8	5	5	10	10	10	10	0	78	7.4
Heat Sensitive Material (High Temp Fit)	5	5	8	10	10	10	10	10	10	0	78	7.15
Deformable insert	5	5	5	10	10	10	10	10	10	0	75	7
Foam	10	10	8	5	5	10	10	10	10	-5(c)	73	6.9
Air/Pneumatic	10	5	8	10	5	10	10	5	1	0	64	6.7
EAP w/Feedback Control	10	10	1	5	5	5	1	5	1	5(d)	53	6.65
Surface Adhesive	10	10	1	5	5	10	5	5	10	0	61	6.55
Air/Pneumatic w/Feedback Control	10	10	1	10	5	5	1	5	1	0	48	6.4
Shape Memory Alloy w/Feedback Control	10	10	1	5	5	5	1	5	1	5(e)	48	6.15
Heat Sensitive Material w/Feedback Control	10	10	1	5	5	5	1	5	1	0	43	5.65
Heat Sensitive Material (Facial Temp)	5	5	8	1	10	10	10	5	10	0	64	5.55

Potential technology sources for encapsulated gels include sleep apnea mask manufacturers such as Respironics, Resmed, and Hans Rudolph. In addition, Foster-Miller has experience developing encapsulated gels and Gel Smart provides a range of commercially available gel products. A unique technology identified in the survey was the Nasal Lite mask from Respironics. It is recommended to further consider this product in future efforts because it provides the potential for both a custom fit and pressure sensitive seal. A high temperature activated custom fit approach is required due to the range of operational and storage environments that the mask will be deployed. The JSGPM performance specification requires the mask function over the temperature range of -32 to 49°C. It is recommended to assess the effect of adverse environmental exposures on the physical properties and durability of encapsulated gels.

There have been previous efforts to integrate pressure sensitive materials into military APRs. Grove (2007) provided input at a project review meeting regarding previous experience working with gel and air bladder seals. A primary issue has been the membrane thickness that contains the pressure sensitive material. There is a trade-off between durability and compliance to the face. In general, the thinner the membrane the better from a sealing perspective as it will be able to contour to the micro-scale features of the face. However, the thin membrane is easily susceptible to damage. For example, the gel seal used in the Bose Combat Vehicle Crewman Headset is no longer used due to durability issues (Grove, 2007). The membrane must also be elastic. It cannot crease as the pressure sensitive material expands or contracts. Creases in the membrane may become a leak path.

Grove also indicated that gels were not "fluid" enough to conform to facial movements and suggested to investigate encapsulated liquid seals to improve fluidity. The durability of the seal would also be an issue for an air bladder or liquid seal as protection may be compromised if punctured. One option would be to incorporate the pressure sensitive material as a secondary seal. In this concept, the pressure sensitive material would be incorporated on the inner surface of the peripheral seal. The elastomeric faceblank material would still provide a seal on the outer surface.

The active seal systems tended to score the lowest in the trade-off analysis. This was due to the complexity of the system and uncertainty regarding the leak detection system. A leak detection system would be useful to have in the field to verify fit when the mask is donned. Even if an active seal system is not pursued, it is recommended to further assess the potential to monitor leakage based on contact pressure. A real-time sensor could be used to notify the user to manually adjust the mask because of a poor fit during donning. Both TekScan and SPI produce commercial products in a geometry that could be used for preliminary testing.

Four concepts were discussed to actively seal leakage sites based on EAPs; shape memory alloys, shape memory polymers or gels, and a pneumatic system. Although the site and duration of a leak is not known, the time required to elicit a response needs to be considered when comparing the concepts. The shape memory polymers and gels scored lowest. These materials would require resistive heaters to be incorporated into the face seal. It is not expected that the materials would heat and respond in time to seal a transient leak site.

5. COOLING

It has been well documented that there is a thermal discomfort associated with the wear of a respirator (Dubois et al., 1990; Caretti, 2001, Gwosdow et al., 1989; Nielsen et al., 1987; Fox and Dubois, 1993). Thus, a respirator that provides facial cooling may increase mask wear time. Facial cooling would also reduce the sweat rate potentially leading to an improvement in protection factor by reducing mask slippage. The market survey focused on two cooling technologies: (1) thermoelectric coolers and (2) miniature fans and blowers. Miniature fans and blowers could also help improve protection by creating positive pressure across the facial seal. Thermoelectric cooling is discussed in Section 5.1 and fans/blowers in Section 5.2.

5.1 Thermoelectric Cooling

Thermoelectric coolers (TECs) have found application primarily in electronics cooling (e.g., camera detectors, lasers, microprocessors). A TEC is a solid-state device that generates a thermal gradient when a direct current is applied. This phenomenon, known as the Peltier effect, is illustrated in Figure 16. One side of the TEC becomes hot and the other side becomes cool when the current is applied. Heat is adsorbed on the cool side and dissipated environment on the hot side. The thermoelectric module itself is generally small and lightweight. However, in addition to the module, a complete assembly also requires the power supply and heat transfer plates/fins as shown in Figure 17. Fans are typically added to enhance heat transfer if cooling the air. The TEC will operate most efficiently when the heat sink is able to dissipate heat quickly. These heat sinks and fans will add to the size, weight, and power requirement of the cooling unit. A thermocouple and a controller can be used to control the cooling rate which is adjusted by varying the current. The amount of cooling provided is a function of the ambient temperature, temperature difference between the hot and cold plates, efficiency of the heat dissipation system, and the applied current. TECs can be connected in series to increase the maximum heat sink.

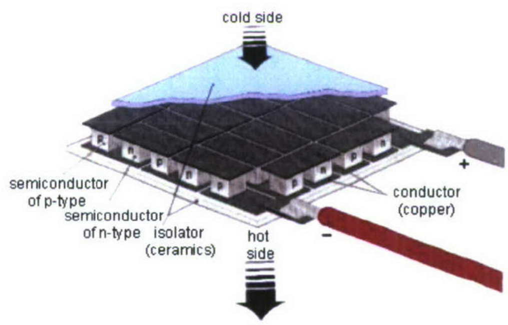

Figure 16. Typical Thermoelectric Module (Rudometov, 2004)

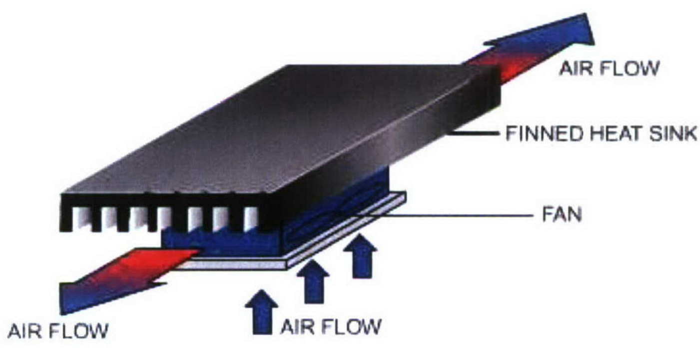

Figure 17. Diagram of a Forced Convection Heat Sink System (FerroTec, 2006)

Advantages of thermoelectric devices include their durability, low maintenance, lack of hazardous by-products, and constant cooling rate. Thermoelectrics are durable because they do not have any moving parts. Their ability to provide a constant cooling rate makes them attractive for personal cooling as phase change materials degrade over time. Thermoelectrics can also be used for heating by reversing the polarity of the current.

The primary disadvantages are their need for large amounts of power relative to that available for dismounted soldiers and they are relatively inefficient. The coefficient of performance (COP) is commonly used to compare TECs and is defined as the ratio of heat adsorbed to the input power. The COP for TECs typically ranges from 0.4 to 0.7. In comparison, vapor compression devices have COPs in the range of 2 to 3 (NAS, 2003; Wolfson and Masadi, 1993). Because of their inefficiency, TECs are best suited for applications requiring less than 100 W of cooling. They are susceptible to damage from moisture which can corrode or short circuit the device. However, sealants can be used to prevent moisture from contacting the thermoelectric material.

Thermoelectric coolers have been previously evaluated for whole-body personal cooling but power requirements and total weight limited the usefulness (Wolfson and Masadi, 1993). The systems that were evaluated provided about 200 to 300 W of cooling with coefficients of performance ranging from 0.24 to 0.38. The amount of cooling provided per unit mass of the device ranged from 9 to 31 W/kg. It was concluded that the TEC devices evaluated were not feasible for dismounted soldiers due to the high power requirements. The authors estimated that up to 10 kg of batteries would be needed to operate each system for 3 to 4 hours.

Thermoelectric coolers potentially are more useful for facial cooling as the load is reduced. In fact, an approach is described in U.S. Patent No. 6,382,208. The concept is shown in Figure 18. The TEC is mounted above the exhalation valve and contains fans inside and outside of the mask to promote heat exchange. The outside fan is labeled number 50 on the schematic. The battery pack is shown connected to the side of the visor. The cooling in the mask also reduces the humidity within the mask. The authors note that a wicking material is used to collect moisture that drips off of the cooling surface. The thermoelectric device can be operated continuously or facial temperature monitored to provide feedback control. The latter may extend the life of the power supply. No information is provided in the patent as to the weight, power requirements, or cooling provided by the TEC.

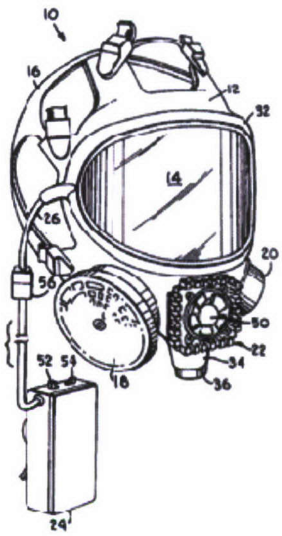

Figure 18. Schematic of Thermoelectric Cooling Device Integrated into Respirator (taken from U.S. Patent No. 6,382,208)

TE Technologies (Traverse City, MI) integrated a TEC device into a helmet for motorcyclists (Buist and Streitwieser, 1988) for head cooling. A liquid cushion was integrated into the helmet that was in contact with the wearer's head. A 12 V thermoelectric module was used to remove heat from the liquid cushion. The heat was dissipated through a finned heat sink that was located on top of the helmet. The device operated on up to 2 A of current and had a weight of only 255 g.

Two other products were identified that utilize thermoelectric cooling technology for the purpose of personal cooling. Both provide a source of portable, lightweight, battery-powered cooling. The Personal Cooling Device (PCD), manufactured by It's Kool, uses thermoelectric cooling technology to provide a "pulsed" cooling effect (It's Kool, 2006). One PCD (Figure 19) can provide up to 10 hours of pulsed cooling. The It's Kool device is user-controlled and, thus, provides cooling at the touch of a button. The lightweight and flexible PCD unit allows for integration into a number of areas, such as a hat, helmet, goggles, article of clothing, etc. No specific details are provided as to the amount of cooling provided by the PCD.

Figure 19. It's Kool™ Personal Cooling Device (It's Kool™, 2006)

The Sharper Image (San Francisco, CA) Personal Warm+Cool System (Figure 20) is another portable cooler that operates on the Peltier effect. This device, powered by three C batteries, is worn around the neck and can provide either a warming or cooling effect. The dual conditioning effect is made possible by turning a knob on the device which changes the direction of the current, reversing the flow of electrons in the system. The device weighs eight ounces and is connected to a battery pack that is 7.6 x 10.2 cm and can be worn on the belt. This device was tested by Caretti (2001) as part of an assessment of personal cooling technologies used to alleviate mask thermal discomfort. Tests were conducted with and without the device by subjects wearing a M40A1 mask and JSLIST protective suit. Caretti concluded that the device alone did not eliminate thermal discomfort in the mask for subjects wearing chemical and biological protective clothing.

Figure 20. The Sharper Image Personal Warm+Cool System
(The Sharper Image UK, 2006)

A respirator offers a limited number of locations for the placement of the TEC. The TEC module must be placed such that the heat sink can dissipate heat to the ambient environment. Potential concepts are described below:

- Integrate thermoelectric device into faceblank as described in U.S. Patent No. 6,382,208 to cool the interior of the mask.

- Integrate thermoelectric device into the canister connection to the mask. This approach would eliminate the need for a fan on the inside of the mask as the inhaled air would be drawn over the cooling element to enhance heat transfer.

- Use a thermoelectric device to cool a gel that is circulated through the mask harness. This concept would be similar to the racing helmet designed by TE Technologies. This approach is advantageous as no modification is needed to the faceblank.

- Use a thermoelectric device to cool a gel that is circulated through the peripheral seal. As discussed previously, this concept is also advantageous as it provides cooling directly to the region of the face covered by the peripheral seal.

- Integrate miniature thermoelectric device into the facial seal at multiple locations. This may be advantageous since it would be in direct contact with the skin. The devices could provide continuous cooling, intermittent cooling control based on skin temperature, or provide cooling on demand similar to the It's Kool device. Scanlan and Roberts (2001) indicate that skin temperature only increases around the peripheral seal during wear of an APR.

In the first two concepts, the thermoelectric device would be used to cool the air either delivered to or inside of the mask. Commercial-off-the-shelf assemblies with cooling rates in the range of 20 to 30 W were targeted. An example of an assembly is shown in Figure 21 and consists of the thermoelectric module, heat transfer plates/fins, and fans. Assemblies were identified from Custom Thermoelectric (Bishopville, MD), Supercool (San Rafael, CA), Watronix (West Hills, CA), Thermoelectric Corporation of America (TECA) (Chicago, IL), Marlow Industries (Dallas, TX), MelCor (Trenton, NJ), and TE Technologies (Traverse City, MI). Companies such as Ferrotec (Bedford, MA) offer the capability to develop custom assemblies. Information was obtained regarding their physical size and power requirements. The results are summarized in Table 9. The average dimensions of the assemblies are approximately 13 x 10 x 11 cm with an average weight of 1.1 kg. All of the assemblies operate on 12 V DC. The average cooling provided is 24 W and the average power supplied is nearly 50 W. This is well in excess of the 10-12 W budgeted in the near term for complete body cooling (NAS, 2003). The battery weight required to power the assembly for 12 hours was estimated assuming that current battery technologies can provide 300 W-hr/kg. Note that the wear time requirement for the JSGPM mask is 36 hours and thus only intermittent cooling would be provided. Alternatively the systems could be operated at lower cooling rates to conserve power. Lower cooling rates may be adequate to improve comfort.

Figure 21. Example TEC Air Cooler Assembly (Melcor, 2007)

Table 9. Summary of Thermoelectric Cooler Assemblies

Manufacturer	Model No.	Cooling Rate (W)	LxWxH (cm)	Volume (cm^3)	Power (W)	COP	Weight TEC (kg)	Weight Battery* (kg)	Weight Total (kg)	Q/Total (W/kg)
Supercool	AA-019-12-22	21	8x6x10	485	28	0.75	0.3	1.1	1.4	14.8
Custom Thermoelectric	SC-30-1024	24	6x6x7	311	48	0.50	0.3	1.9	2.3	10.6
Watronix Inc.	INB 140-12-AA	40	15x15x13	2,733	72	0.56	1	2.9	3.9	10.3
Supercool	AA-033-12-22	32	18x14x8	2,102	44	0.72	1.4	1.8	3.2	10.1
Custom Thermoelectric	SC-30-1012	12	6x6x8	311	24	0.50	0.3	1.0	1.3	9.2
TECA	AHP-150XEHC	29	18x9x15	2,506	72	0.40	1.5	2.9	4.4	6.6
Marlow Industries	ST3353	17	11x15x8	1,297	48	0.35	0.8	1.9	2.8	6.2
MelCor	MAA050T-12	15	15x11x11	1,975	36	0.42	1	1.4	2.4	6.1
TE Technology	AC-027	27	15x13x15	2,818	67	0.40	2	2.7	4.7	5.8
TE Technology	LC-035	35	15x13x10	1,950	67	0.52	1.6	2.6	4.2	8.3
MelCor	MAA070T-12	21	17x14x10	2,272	59	0.36	1.82	2.4	4.2	5.0

*Assumes 300 W-hr/kg and 12 hour mission.

The total weight represents that attributed to the assembly and battery. The weight of the assembly is such that it could not be attached directly to the mask. Rather, it would have to be worn on a belt. Similar to a powered air-purifying respirator (PAPR), the canister and TEC could be integrated into a housing. A hose would connect the housing to the facemask. This would increase the breathing resistance of the mask unless a blower was used to provide positive pressure. Blowers are discussed in the following section. It is recognized that the COTS units have not been optimized for the current application. For example, the fan on the cooling side could be eliminated.

Two of the concepts involve the cooling and circulation of a gel. An example of an assembly for cooling liquids from TE Technologies is shown in Figure 22. The physical dimensions and power requirements for this unit, Model LC-035, were provided in Table 9. The heat transfer surface for the liquid side is more compact. However, a miniature pump would be required to circulate the gel.

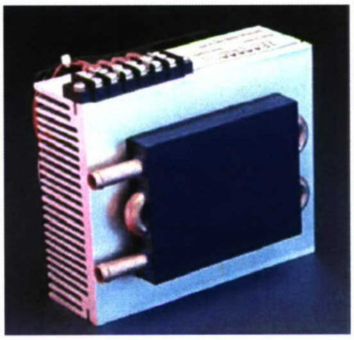

Figure 22. Example Thermoelectric Cooler for Liquids (TE Technologies, 2007)

Recent research has been focused on improving the efficiency of thermoelectric modules. New nano and micro fabrication technologies have led to smaller, lighter, and more efficient TECs. Figure 23 illustrates the resulting difference in size between different fabrication techniques. The TEC on the left measures 16 cm^2 and provides 70 W of cooling. The TEC on the right, manufactured by NanoCoolers (Austin, TX), measures just 0.50 cm^2 and provides the same amount of cooling. Nextreme (Research Triangle Park, NC), a spin-off of the Research Triangle Institute (RTI), is developing the superlattice, which is a semiconductor made up of thousands of very thin (1 to 5 nm) layers of thermoelectric material. According to the Nextreme website, the superlattice (Figure 23) compares extraordinarily well to 'conventional' TECs, providing 20 times the cooling while operating 100 times faster and having a 10 times lower profile. It can provide cooling of as much as 700 W per cm^2 under 58°F. Evident Technologies (Troy, NY) is performing research to apply quantum dots to thermoelectrics to improve their efficiency. Quantum dots have diameters in the range of 2 to 10 nanometers and have electrical and thermal properties that are advantageous relative to the bulk material (Evident Technologies, 2007).

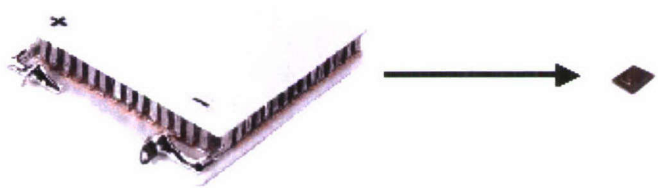

Figure 23. Comparison between Traditional TEC (left) to a NanoCoolers' TEC (right) (NanoCoolers, 2006)

5.2 Miniature Blowers and Fans

Integration of a small, lightweight fan or blower into a respirator mask offers another cooling option. Air circulation within the sealed mask would serve to cool the wearer and also help to create a positive pressure within the mask. A positive pressure would enhance the mask seal and reduce leakage. Blowers provide a higher static pressure and, thus, would provide a better option to generate positive pressure within the mask. However, they also require more power and, in general, tend to be larger than fans.

There are a range of commercially available miniature blowers. Examples are shown in Figure 24 of blowers manufactured by Panasonic (Secaucus, NJ), ETRI (Indian Trail, NC), and Micronel (Vista, CA). Table 10 summarizes the physical dimensions and performance specifications. It includes blowers with a balance between size and power consumption. The blowers in the table represent a combination of the low ends of both available size and power. An increase in the size of a blower or the power consumption would result in a blower with greater capabilities than those listed in the table. The materials of construction of the housing and impellers were generally a thermoplastic. With the exception of the Micronel U51 blowers, the average power requirement was only 2 W and the average flow rate 6 cfm or 170 L/min.

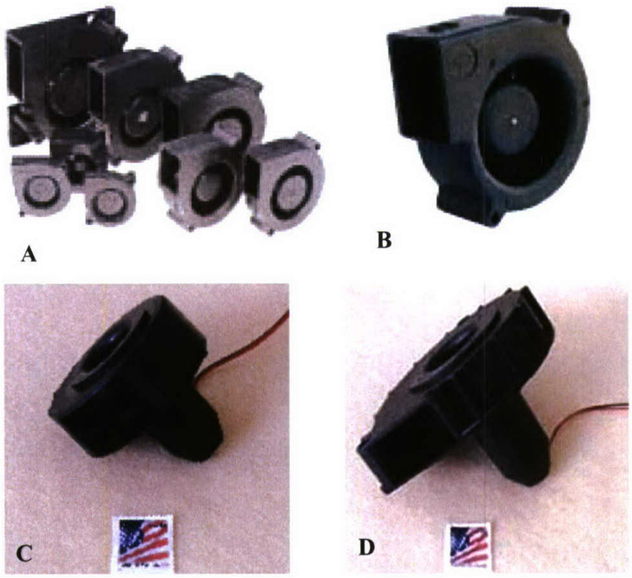

Figure 24. Panasonic (A, from Panasonic, 2006a), ETRI (B, from ETRI, 2006a), Micronel U64 (C, from Micronel 2006a) and Micronel U97 (D, from Micronel 2006b) Miniature Radial Blowers

Table 10. Characteristics of Several Different Miniature Blowers

Manufacturer and Model	**L x W x D (mm)**	**Rated Voltage (V)**	**Power (W)**	**Max. Air Flow (CFM)**	**Max. Static Pressure (in H_2O)**	**Mass (g)**
Panasonic BM4515-04W-B30-L00	44 x 45 x 15	12	1.08	2.6	0.40	27
Panasonic BM4515-04W-B40-L00	44 x 45 x 15	12	1.68	3.0	0.64	27
Panasonic BM4515-04W-B50-L00	44 x 45 x 15	12	2.28	3.5	0.80	27
ETRI 593DL5LP11000	51 x 51 x 15	5	0.7	2.5	0.28	27
ETRI 593DL1LP11000	51 x 51 x 15	12	0.8	2.5	0.28	27
ETRI[b] 593DM5LP11000	51 x 51 x 15	5	1.7	3.2	0.43	27
ETRI 593DM1LP11000	51 x 51 x 15	12	1.2	3.2	0.43	27
Micronel U64LM-006GK-2	64 x 64 x 56	3	2.52	11	1.9	82

Table 10. Characteristics of Several Different Miniature Blowers (Continued)

Manufacturer and Model	L x W x D (mm)	Rated Voltage (V)	Power (W)	Max. Air Flow (CFM)	Max. Static Pressure (in H_2O)	Mass (g)
Micronel U64LM-006GK-2	64 x 64 x 56	6	0.93	8	0.92	82
Micronel U64LM-012GK-2	64 x 64 x 56	12	0.76	7	0.78	82
Micronel U97LM-005KK-1	98 x 98 x 75	5	4.0	17.3	2.6	160
Micronel U97EM-012KK-3	98 x 98 x 75	12	7.4	20.3	3.6	160
Micronel U51	50 x 33	12	20	16	12	80
Micronel U51 D1	50 x 60	12	40	20	18	130
Micronel U51 D2	50 x 97	12	80	23	12	190
Nidec Gamma 26 A33997	51 x 15	12	1.1	2	0.2	28
Nidec Gamma 26 A33999	51 x 15	12	2.0	4	0.65	28
Ametek BLDC 119349	89 x 75 x 70	12	23	17.7	10.1	NA

The BL-50 from Koken Ltd. (Tokyo, Japan), shown in Figure 25, is a half-mask that contains an integral blower that is used to maintain constant pressure within the facepiece during inhalation and exhalation. The pressure within the mask is measured and used to control the blower output. It is operated on power from 4 AA batteries. The weight of the facepiece is only 185 grams and has a battery life of 12 hours (Koken, 2004).

Figure 25. BL-50 Breath-Assisted PAPR (Koken, 2004)

Table 11 summarizes the physical dimensions and performance specifications of the miniature fans identified in the market survey. Operational temperatures commonly ranged from -10 to 70°C. Acal Radiatron (Wokingham, UK) manufactures thermally controlled fans that contain a temperature sensor. Input from the sensor is used to control the rotational speed of the fan.

Table 11. Characteristics of Several Different Miniature Fans

Manufacturer and Model	**L x W x D (mm)**	**Rated Voltage (V)**	**Power (W)**	**Max. Air Flow (CFM)**	**Mass (g)**
Sofasco D5010 D5010V12M	50x50x10	12	1.2	8.8	20
Micronel FMA2505A	25x25x7	5	0.2	0.82	6
Micronel FMB3005A	30x30x6.5	5	0.25	1.7	6
Micronel D241 (axial fan)	24x30	12	0.26	2.1	15
Nidec C34237	25x25x10	12	0.6	0.8	10
Nidec U40X12MLZ7	40x40x10	12	0.6	3.9	NA
Nidec U40X12MHZ7	40x40x10	12	1.2	6.7	NA

Piezoelectric fans (Figure 26) are being developed for small electronics cooling. The physical size of the fans described in Table 11 prevents them from being integrated into portable electronics such as mobile phones. The Cooling Technologies Research Center at Purdue University is performing research to characterize piezoelectric fans. Applying an alternating current to the piezoelectric fan causes it to flap back and forth. Piezoelectric fans are much quieter than standard rotary fans. PiezoFans LLC (Indianapolis, IN) offers the capability to custom design and manufacture piezoelectric fans.

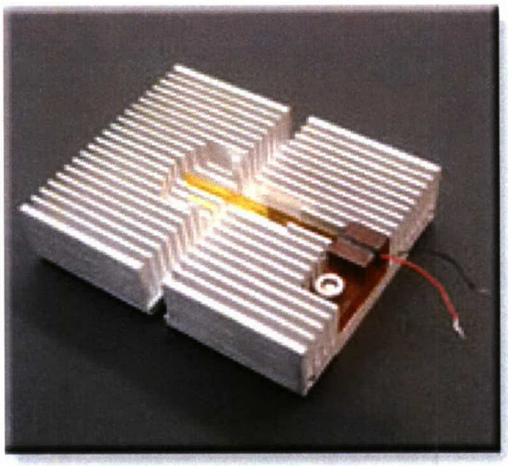

Figure 26. Piezoelectric Fan (PiezoFans, 2007)

The concept of incorporating a miniature fan into a sporting goggle has been adopted by Smith Optics (Ketchum, ID), a manufacturer of high-quality sporting goggles. They have developed a special Turbo Fan series (Figure 27), a collection of goggles equipped with a lightweight fan to eliminate fogging. The fan, which can operate on the low setting for up to 50 hours with AAA batteries, draws in ambient air and directs it toward the mask lens (Smith, 2006). The battery pack for the fan is located on the side of the head band, as seen in the figure.

Figure 27. Smith Optics Cascade Snow Goggles with Micro Electronic Fan (Smith, 2006)

In summary, multiple fans could be integrated into a mask to create an air management system. A fully integrated control system with temperature sensors to identify hot spots and pressure sensors to identify potential areas of inward leakage could be used to adequately cool and protect the wearer. A blower could also be used to draw in ambient air through a filter. This would create a positive pressure in the mask and prevent inward leakage, but also increase the power requirement.

5.3 Vapor Compression

The U.S. Army Natick Soldier Center is exploring light weight systems based on vapor compression. Two systems have been developed that offer 115 to 120 W of cooling with an electrical power requirement of 50 W, weight of 1.8 kg, and volume of 2,800 cm^3 (Natick, 2004). These systems, developed by Foster-Miller and Aspen Systems (Marlborough, MA), have coefficients of performance an order of magnitude higher than some of the thermoelectric systems described in Section 5.1. An example of a miniature compressor from Aspen Systems is shown in Figure 28. It has a diameter of 5 cm and a length of 7 cm. It weighs only 0.6 kg. It has been integrated into a backpack configured system that provides 300 W of cooling and weighs only 4.1 kg. The compression system is used to cool water that is circulated through a tube-lined garment. Aspens Systems has developed models that provide cooling capacities ranging from 120 to 400 W.

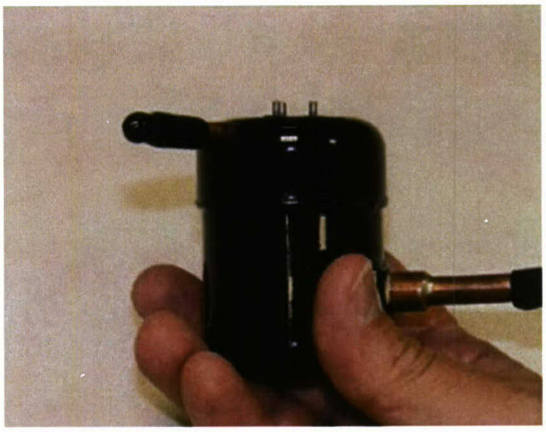

Figure 28. Miniature Compressor from Aspen Systems (Aspen Systems, 2007)

Integrated mesoscopic cooler circuits (IMCCs) are a unique example of a vapor compression system being developed at the University of Illinois (Shannon et al., 1999). The flexible and inter-connectable IMCC patches (Figure 29) are manufactured by combining thin-film and silicon-based MEMS fabrication processes. The patch, each of which represents a complete cooling system, measures just 100 mm^2 and 2.5 mm thick (Shannon et al., 1999). One patch is designed to have a cooling capacity of 3 W and operate between 20°C (evaporator temperature) and 50°C (condenser temperature). Power consumption ranges from 0.5 W to 0.75 W and the unit weight is 40 grams. Coefficients of performance are predicted to be around four to six.

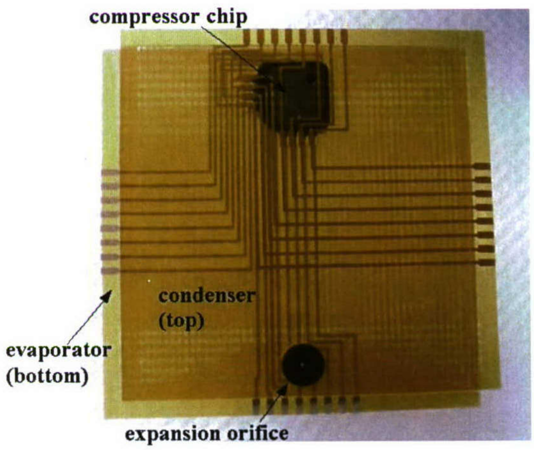

Figure 29. Integrated Mesoscopic Cooler Circuit
(The Shannon Research Group, 2006)

IMMCs can be used as a form of active cooling in various clothing garments. Much of the work in developing IMCCs was funded by DARPA to be applied to cooling vests for military personnel (Shannon et al., 1999). Numerous IMCC patches could be incorporated into the fabric of the vest, allowing for effective cooling in a hot, desert environment. Application of IMCCs to a gas mask can be explored. As with TECs, heat must be effectively removed from the cooling unit. Therefore, the most applicable location for an IMCC would be within the material of the mask. A power source would also be required for IMCC operation.

6. NON-CARBON BASED FILTRATION

Current respirator filters contain impregnated activated carbon to remove toxic vapors or gases. Exposure to adverse environmental conditions can degrade the performance of the carbon over time. This leads to conservative change-out schedules. In addition, activated carbon is not effective against all TICs. The objective was to identify non-carbon based filtration systems that offer improved protection capabilities. Improvement was defined as an increase in capacity, reduced environmental degradation, or broader protection against TICs. Two non-carbon based filtration technologies were considered: (1) photocatalytic oxidation, and (2) catalytic oxidation.

6.1 Photocatalytic Oxidation

Photocatalytic oxidation (PCO) has been used to remove contaminants from both air and water. The reactor contains a titanium dioxide (TiO_2) catalyst bed that is exposed to ultraviolet (UV) light to break down the contaminant. For example, hydrocarbons will be reduced to water and carbon dioxide. It is desirable for the substrate to have a large surface area and good UV transmission. The TiO_2 catalyst has been applied to various substrates including glass fibers, glass beads, and honeycomb monoliths (Wang et al., 2007; Pirich et al., 2001). Factors that affect the removal rate include residence time, inlet contaminant concentration, illumination intensity, and relative humidity. Several studies have been performed to characterize the capability of PCO systems to remove chemical and biological warfare agents and TICs (Vorontov et al., 2002; Pirich et al., 2001).

A report by Pirich et al. (2001) describes a prototype Personal Environmental Protection System (PEPS) for removal of chemical agents and biological pathogens before inhalation. TiO_2 was applied to three support structures: hydrogel filters, glass beaded foam filters (GBFF), and silica based HEPA filters. The filters were challenged with Bg spores and dimethylmethyl phosphonate (DMMP). The UV light operated on 6 W of power. The TiO_2 coated HEPA media provided the best balance between aerosol collection efficiency and air flow resistance. The collection efficiency was greater than 99.995% for 1.0 μm PSL spheres and Bg spores. HEPA filters have efficiencies of greater than 99.97% and, thus, high aerosol capture efficiency was expected with this type of filter architecture. Filter swatches with a diameter of approximately 7.6 cm were tested. A three log reduction in culturable organisms was observed after a 20-minute exposure to UV light as compared to that observed without the UV light.

Pirich et al. (2001) also assessed the DMMP gas life of the TiO_2 coated HEPA media and GBFF. Initial tests were performed at a challenge concentration of 500 to 1,000 mg/m^3, a flow rate of 50 L/min, and a breakthrough concentration of 0.04 mg/m^3. These test conditions are similar to that defined in the C2A1 canister specification. For both the TiO_2 coated HEPA media and GBFF, the downstream concentration was at least 50 percent of the challenge within15 minutes of testing. Breakthrough (a downstream concentration of 0.04

mg/m^3) was immediate. Tests performed with and without UV excitation did not result in significantly different gas lives. It was determined that additional surface area was needed for vapor adsorption. However, the GBFF and HEPA media architectures were not viable approaches due to limitations in pressure drop or system size.

Obee et al. (1998) also assessed the removal of DMMP from the gas phase. The inlet concentration was 90 ppm. The decomposition products in the effluent were water, carbon monoxide, and carbon dioxide. The catalyst was deactivated by deposition of products methylphosphonic and phosphate on the surface. Rinsing with water regenerated the catalyst. Pirich et al. (2001) indicated that poisoning of the catalyst by collected contaminants was prevented by infrequent rinsing of the filters with H_2O.

Vorontsov et al. (2002) assessed the removal of a mustard simulant from both the air and water phase using PCO. In the gas phase, the inlet concentration of the simulant was 76 ppm and tests were performed over inlet temperatures from 23 to 70°C. The PCO plate had an area of 9 cm^2 and the flow rate through the system was 30 cm^3/min. The system converted about 90% of the simulant. The highest conversions were observed at high humidity. The only gaseous breakdown product observed in the outlet was carbon dioxide. The other breakdown products were adsorbed onto the surface of the catalyst, resulting in a deactivation of the catalyst. Negative control tests were performed without UV excitation to demonstrate it is needed for destruction of the simulant. Voronstov et al. (2004) also studied the removal of a VX simulant from the aqueous phase.

Wang et al. (2007) characterized the ability of PCO to convert nitrogen oxide to nitrogen dioxide. The UV light source was a 125 W Hg-arc lamp. A residence time of at least 15 seconds was needed to maximize conversion. At an inlet concentration of about 150 ppm (the highest tested), the conversion efficiency was only 27%. The conversion increased as the inlet concentration decreased. The deactivation of the catalyst was attributed to the adsorption of nitrate onto the surface. The catalyst could be heated to 500°C to regenerate. Canela et al. (1998) also observed catalyst degradation when scrubbing another TIC, hydrogen sulfide, from air.

Park and Kim (2004) used a polyester fabric substrate for the TiO_2 catalyst to improve the particulate collection efficiency. The reactor measured 80 x 25 x 30 cm. The authors studied the removal of toluene. The challenge concentration ranged from 2 to 20 ppm and the flow rate ranged from 0.5 to 7 L/min. As expected, they observed that the vapor removal improved with increased light intensity and residence time. Their conclusions regarding the effect of humidity are of interest. The removal efficiency improved with increasing humidity up to a level of about 55% and then it began to decrease. The authors concluded that the water begins to reduce the reaction rate as humidity continues to increase because it competes for the activation sites.

Turchi and Rabago (1995) characterized the ability of a PCO system to remove volatile organic compounds (VOCs). The test chemicals were isopropanol, acetone, and methanol at a concentration of 100 ppm. The PCO removed over 95% of the VOCs if the residence time was at least 3 seconds. The VOCs were converted to carbon dioxide and water.

The UV light source had a power of only 8 W. The reactor temperature was varied and it was observed that increasing the temperature resulted in an increase in the reaction rate and conversion.

PCO devices have been designed and implemented in HVAC systems to remove nuisance vapors and biological contamination. Chen et al. (2005) evaluated a PCO system containing two TiO_2-coated honeycomb monoliths irradiated by three UV lamps designed for in-duct mounting. The system was challenged with 16 VOCs in 6 chemical categories (alkane, aromatic, chlorocarbon, aldehyde, ketone, and alcohol). The study concluded that sorption based filtration provided the best removal efficiencies for most of the challenge compounds. Ginestet et al. (2005) described a PCO system designed to remove VOC (toluene, ethanol and acetone) from aircraft cabins. The degree of destruction of the VOC depended on the flow rate through the PCO. Multiple passes through the device were used to improve the removal efficiency. Yu et al. (2005) demonstrated the potential to use PCO systems to control VOC contamination in HVAC systems. A titania coated mechanical filter and two commercial photocatalyst filters were evaluated for several air exchange rates to remove toluene and formaldehyde.

Numerous studies have been performed to characterized PCO systems for removal of bacteria and fungal spores with some conflicting results. Jacoby et al. (1998) deposited specimens of *E. coli* on glass slides and on TiO_2 (DeGussa P25) coated slides. Both were exposed to UV radiation for 75 hours. Little degradation of the bacteria occurred with UV radiation alone, but in the presence of both the catalyst and UV radiation the bacteria were oxidized. Wolfrum et al. (2002) demonstrated that *E. coli*, *M. luteus*, *B. subtilis* (vegetative cells and spores), and *A. niger* were oxidized in a PCO reactor after exposure for 1 to 2 days. The fungal spores were the most difficult to oxidize. Lin and Li (2003) evaluated the germicidal capacity of PCO filters on biological areosols. A commercial TiO_2 filter (DAIKIN, Air filter No. 1119589, Japan) was used with UV excitation from an 8 W and 36 W UV lamp. Four bioaerosols including *E. coli*, *B. subtilis*), *C. famata* var. *flareri*, and *P. citrinium* were used in the study. The bacteria were ~1 μm in diameter and the yeast and fungus aerosol particles were ~2.4 μm in diameter. Tests compared the viability of the bioaerosol following filtration by the PCO filter with and without UV excitation. No statistically significant decrease in bioaerosol viability was detected when the PCO was excited using the 8 W lamp. The 36 W lamp alone exhibited germicidal properties for the *E. coli.* bioaerosol, but showed no significant effect on the other three bioaerosol species.

In summary, data is lacking in the literature that demonstrates the performance of PCO systems against chemical warfare agents or simulants and TICs at challenge levels specified in the C2A1 military specification. The rate of removal is a strong function of residence time in the reactor. Multiple pass systems have been designed to improve removal efficiency. It has been shown to be an effective technology for removing low levels of VOCs in HVAC applications. A commonly reported problem associated with PCO is the deactivation of the catalyst as the breakdown products adsorb on the surface. Another issue with PCO is that the breakdown products in the effluent can also be harmful. For example, hydrogen chloride will likely be a product if the inlet contains chlorinated compounds (Turchi and Rabago, 1995). Thus, it is required to have a filter downstream of the PCO to remove toxic by-products. VOCs are converted to carbon dioxide and water which also may need to be removed depending on the concentration.

The primary advantage from an individual protection viewpoint is the modest power requirement. The only power required is that to operate the UV light source. For example, the UV light source in the portable system described by Pirich et al. (2001) was powered by a 9 V battery. PCO is not expected to improve the collection efficiency of biological agents. However, it has been shown that biological agents can be oxidized once captured. However, this would likely not reduce the hazard of handling the filter/reactor as the outer surfaces would still be contaminated. In addition, there would be the added burden to continually clean degradation products from the catalyst surface.

6.2 Catalytic Oxidation

Catalytic oxidation (CATOX) has received significant attention in the literature for collective protection applications (Balboa et al., 2004; Rosin, 1995; Agarwal and Spivey, 1993; Michalakos et al., 2002). CATOX systems consist of a metallic catalyst such as alumina, copper, or zinc impregnated onto a substrate. The CATOX systems identified in the literature tended to operate at temperatures ranging from 250 to 350°C. CATOX systems destroy the agents rather than adsorb them on the surface. Thus, the systems do not need to be regenerated. This reduces the logistical supply burden and the need to handle hazardous waste (Michalakos et al., 2002). A polishing filter is needed to remove hazardous by products such as nitrogen oxides or phosphorus, sulfur, or chloride containing compounds. The polishing filter will require replacement. Brown et al. (1995) developed a temperature swing adsorption that heated the adsorbent during the recycle phase and the desorbed contaminants were passed through the CATOX reactor for destruction.

CATOX is capable of providing protection against both chemical and biological agents, however, the literature identified focused primarily on performance against chemical warfare agents and TICs. Balboa et al. (2004) assessed the ability of nine different catalyst materials to remove ammonia, ethylene oxide, formaldehyde, hexafluoropropene, chloroethyl ethyl sulfide (CEES) and dimethyl methylphosphonate (DMMP). The hexafluoropropene required the highest catalyst operating temperature (350°C) to attain 99% destruction and was the design limiting chemical. This illustrates the high temperature of operation. The CATOX system attained greater than 99% destruction of ammonia, ethylene oxide, formaldehyde, and hexafluoropropene and greater than 99.99% destruction of CEES and DMMP. The effluent contained 15 ppm of NO_x when decomposing ammonia, illustrating the need for a polishing filter downstream of the CATOX reactor.

Agarwal and Spivey (1993) assess the performance of a catalytic microreactor for destruction of cyanogen chloride (CK). The degradation of CK appeared be a hydrolysis as water vapor was required in the feed stream of the reactor. The effluent contained CO when run with a dry feed stream. Wen et al. (1996) also indicated that water vapor is needed in the feed stream to degrade halogen containing compounds.

Rossin (1995) demonstrated the performance of a CATOX system for destruction of hydrogen cyanide (AC). The inlet concentration of AC ranged from 200 to 20,000 ppm and initial catalyst temperatures ranged from 200°C to 310°C. The decomposition products in the effluent were CO_2, NO_x, and N_2O. Effluent concentrations varied depending on inlet concentration and reactor temperature. The catalyst temperature increases during removal due to the heat of reaction. Tests were performed over a range of challenge concentrations to simulate various scenarios. At the highest challenge concentration of 20,000 ppm, the catalyst temperature increased to 660°C and the effluent contained high concentrations of NO_x (~18,000 ppm).

This high temperature limits the potential application to individual protection. In vehicle protection applications, heat from the engine exhaust is utilized to raise the catalyst to operating temperature. The reactor temperature must be maintained at a minimum temperature during operation to ensure the reactor will "light" when challenged. In a dismounted mode, power would be required to heat the inlet air and reactor and to cool the effluent. As an example, it would require at least 160 W just to heat dry air from 45 to 250°C. This assumes a constant heat capacity of 1020 J/kg-K for dry air and a mass flow rate of 7.8×10^{-4} kg/s (equal to 40 L/min under ambient conditions). To reduce power requirements, Powell et al. (2006) used a heat exchange to preheat the incoming air using the hot gases exiting the reactor. There would also be a start-up to permit the catalyst to reach temperature. In comparison, the carbon filter used in current protection systems is ready for immediate use. Current mask systems are to be donned and functional within 10 seconds. The only protection provided during startup would be that provided by the polishing filter. The need for a polishing filter offsets the logistical advantage of replacing current carbon-based filtration systems.

6.3 Summary

Both of the technologies reviewed have benefits and issues as to how they apply to individual protection. The issues tend to outweigh the benefits for both. The advantages and disadvantages of each are summarized in Table 12. The power requirements for catalytic oxidation and non-thermal plasma are limiting. Photocatalytic oxidation provides the more likely application to individual protection based on the modest power requirement. For example, the UV light source used in the PEPS was operated on a 9-V battery. However, studies have shown that degradation of the catalyst due to adsorption of by products is problematic. Although it has been shown that rinsing with water often regenerates the catalyst, this may not be reasonable in the field. Photocatalytic oxidation systems are effective at low level concentrations but performance equivalent to that of a C2A1 canister has not been demonstrated. Both of the technologies require a polishing filter downstream of the reactor to absorb toxic decomposition products.

Table 12. Advantages and Disadvantages of Applying Photocatalytic Oxidation and Catalytic Oxidation to Individual Protection

Technology	Advantages	Disadvantages
Photocatalytic Oxidation	• Low power requirement • Destroys biological agents	• Need for polishing filter to remove hazardous breakdown products • Catalyst degradation • Equivalent performance to C2A1 canister not demonstrated • CO_2 generation
Catalytic Oxidation	• Operational life • Increased capacity relative to carbon-based filters	• Need for polishing filter to remove hazardous breakdown products • Power requirements • High temperature

7. CONCLUSIONS AND RECOMMENDATIONS

The technology survey to improve the facial seal focused on materials that respond to temperature, pressure, or voltage. Example materials identified include shape memory polymers, temperature activated gels, pressure sensitive materials (i.e., foam, gels, air bladders), electroactive polymers, and shape memory alloys. Three generic seal systems were defined: (1) custom fit, (2) passive, and (3) active. The concept for the custom fit seal system is to integrate a responsive material into the seal that can be "molded" to the macroscopic features of the wearer's face. A passive fit system would provide a custom fit and also have the potential to improve the dynamic fit. The primary technologies considered here were the pressure responsive materials such as gels. An active fit system is differentiated because a leakage sensor is needed to identify the leakage. An integrated microprocessor would then be used to control a responsive material, such as an electroactive polymer, at the mask periphery.

A trade-off analysis was performed to select the most promising concepts/ technologies for further consideration. Criteria used in the analysis included, but were not limited to, fit enhancement, ease of use, environmental operability, and maturity level. The passive seal systems tended to have the highest scores. This can be attributed to three primary factors: (1) no power required, (2) potential to respond to dynamic leakage without the need for a leakage sensor, and (3) maturity of the technology. Of the pressure sensitive materials, the encapsulated gels scored the highest. They were considered more durable than air bladders and foams. In addition, the literature indicated that gel seals dissipated heat better than foam seals and, thus, were expected to be more comfortable. Thus, it is recommended to further assess the integration of an encapsulated gel into a military APR.

Manufacturers of sleep apnea masks represent a primary technology source for encapsulated gels or other pressure sensitive approaches. The Nasal Lite mask from Respironics was a unique technology identified in the market survey and it is recommended to consider it for future efforts. Based on input from Grove (2007), it is also recommended to further investigate encapsulated liquids as their fluidity may enhance compliance. The membrane that encapsulates the gel or liquid will be an important area of development. The membrane must also be elastic. It cannot crease as the pressure sensitive material expands or contracts. Creases in the membrane may become a leak path. Also, the JSGPM performance specification requires the mask function over the temperature range of -32 to 49°C. The effect of low temperature exposure on the physical properties of the gels requires characterization.

The active seal systems tended to score the lowest in the trade-off analysis. This was due to the complexity of the system. However, it is recommended to focus the development of an active system on the leak detection system. This system would be beneficial even if not used to control an active leak system. It could be used to notify the wearer of a proper or improper fit after donning. This would permit the wearer to manually adjust the respirator until an adequate fit was obtained. Technology sources were identified that manufacture or develop tactile pressure sensors. In addition, polymeric tactile pressure sensors are being developed for artificial skin on robots.

Thermoelectric devices and miniature blowers and fans were reviewed for cooling applications. Several commercial-off-the-shelf blowers and fans were identified in the market survey offer potential short term solutions for cooling and protection enhancement. An example is the mask-mounted blower from Koken Ltd. This blower maintains positive pressure within the mask and has operates for up to 12 hours on 4 AA batteries. Miniature fans are being developed for cooling small, portable electronics such as cell phones. Future developments should continue to be monitored. Piezoelectric fans are an example technology that are quieter than rotary fans, light-weight, and consume little power.

The ability of thermoelectric devices to provide a constant cooling rate makes them attractive for personal cooling. However, the primary disadvantage is their inefficiency. The coefficient of performance (COP), defined as the ratio of heat adsorbed to the input power, is generally in the range of 0.3 to 0.7. A thermoelectric cooling assembly generally consists of the thermoelectric module, heat plates or fins, and a fan for air applications. Commercial-off-the-shelf assemblies that offered 20 to 30 W of cooling were targeted in the survey. Power requirements and weight limit the application to respirators. However, it is recognized that the off-the-shelf systems are not optimized for the current application. In addition, intermittent operation of the system, either through temperature feedback control or user input, may reduce power requirements.

The open-literature regarding photocatalytic and catalytic oxidation was reviewed to assess the feasibility of integration into an individual protection system. The issues tended to outweigh the benefits for both technologies. The power requirement for catalytic oxidation is limiting due to the need to operate at high temperatures. Photocatalytic oxidation provides the more likely application to individual protection based on the modest power requirement. For example, the ultraviolet (UV) light source used in the prototype Personal Environmental

Protection System (PEPS) consumed only 5 W. However, studies have shown that degradation of the catalyst due to adsorption of by products is problematic. Although it has been shown that rinsing with water often regenerates the catalyst, this may not be reasonable in the field. Also, the breakdown products can be hazardous themselves (e.g., HCl, CO_2, etc.). Photocatalytic oxidation systems have been shown to be effective at low level concentrations but performance equivalent to that of a C2A1 canister has not been demonstrated. Both of the technologies require a polishing filter downstream of the reactor to absorb toxic decomposition products. This likely increases the inhalation resistance and adds to the logistical burden.

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APPENDIX A

KEY WORDS USED IN TECHNOLOGY SURVEY

FACIAL SEAL SEARCH STRATEGY

b 411; sf allscience not patents; s (((smart or intelligent or responsive)()material? ?) OR ((polymer or sol or morph)()(gel or gels)) OR hydrogel? ? OR (dielectric()elastomer? ?) OR (gecko or (Van(1w)Waals))) AND (mask? ? or respirator? ? or prosthe?)

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SYSTEM:OS  - DIALOG OneSearch
File 155:MEDLINE(R) 1951-2006/Jun 08 (c) format only 2006 Dialog
File 103:Energy SciTec 1974-2006/Apr B2 (c) 2006 Contains copyrighted material
File   6:NTIS 1964-2006/May W3 (c) 2006 NTIS, Intl Cpyrght All Rights Res
File 266:FEDRIP 2005/Dec Comp & dist by NTIS, Intl Copyright All Rights Res
File 587:Jane`s Defense&Aerospace 2006/Jun W1 (c) 2006 Jane`s Information Group
File 167:Medical Device Register (R) 1999 (c) 2006 The Thomson Corporation
File 104:AeroBase 1999-2006/Mar (c) 2006 Contains copyrighted material
File 369:New Scientist 1994-2006/Jun W1 (c) 2006 Reed Business Information Ltd.
File 198:Health Devices Alerts(R) 1977-2006/May W1 (c) 2006 ECRI-nonprft agncy
File 370:Science 1996-1999/Jul W3 (c) 1999 AAAS
File 293:Engineered Materials Abstracts 1966-2006/May (c) 2006 CSA.
File 323:RAPRA Rubber & Plastics 1972-2006/May (c) 2006 RAPRA Technology Ltd
File 636:Gale Group Newsletter DB(TM) 1987-2006/Jun 07 (c) 2006 The Gale Group
File 136:BioEngineering Abstracts 1966-2006/Apr (c) 2006 CSA.
File 144:Pascal 1973-2006/May W2 (c) 2006 INIST/CNRS
File  73:EMBASE 1974-2006/Jun 09 (c) 2006 Elsevier Science B.V.
File   8:Ei Compendex(R) 1970-2006/May W4 (c) 2006 Elsevier Eng.  Info. Inc.
File   2:INSPEC 1898-2006/May W4 (c) 2006 Institution of Electrical Engineers
File   5:Biosis Previews(R) 1969-2006/Jun W1 (c) 2006 The Thomson Corporation
File  34:SciSearch(R) Cited Ref Sci 1990-2006/Jun W1 (c) 2006 Inst for Sci Info
File 399:CA SEARCH(R) 1967-2006/UD=14424 (c) 2006 American Chemical Society
>>>CURRENT is not available in file(s): 155 266 167 198
>>>The full file(s) will be searched.
>>>CURRENT4 started
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Set	Items	Description
S1	5908	(SMART OR INTELLIGENT OR RESPONSIVE)()MATERIAL? ?
S2	101582	((POLYMER OR SOL OR MORPH)()(GEL OR GELS)) OR HYDROGEL? ?
S3	291	(DIELECTRIC()ELASTOMER? ?)
S4	146	(GECKO OR (VAN(1W)WAALS))(5N)ADHESIVE? ?
S5	1280	(PRESSURE()SENSITIVE)(5N)POLYMER? ?
S6	693688	(MASK? ? OR RESPIRATOR? ?)
S7	453934	PROSTHE? OR ORTHOTIC? OR ORTHOS?S
S8	2671	(S1:S5) AND (S6 OR S7)
S9	2406	S8 AND PY=2000:2006

S10 1663 S9 AND (((S1:S5)(F)(S6 OR S7))/TI,DE,ID OR ((S1:S5)(5N)(S6 OR S7)))
S11 1656881 DT='REVIEW' OR DT='REVIEW, REPORT'
S12 112719 DT='LITERATURE REVIEW'
S13 118027 DT='BOOK':DT='BOOKS'
S14 46785 DT='MONOGRAPH':DT='MONOGRAPHIC SERIES'
S15 252645 TC='G':TC='HISTORICAL' OR TC='LITERATURE REVIEW/BIBLIOGRAPHY'
S16 40 S10 AND (S11:S15)
S17 39 RD (unique items)
S0 56 KEEP ITEMS FROM SET S8 FROM FILES 266,587,167,104,369,198,370,293,323
S19 55 RD S0 (unique items)
S20 199 (S10 NOT (S0 OR S16)) AND S6
S21 190 S20/ENG OR (S20 AND LA=ENGLISH)
S22 135 RD (unique items)
S23 38 (S10 AND (FIT OR FITTING OR COMFORT? OR SEAL?)) NOT (S0 OR S16 OR S20)
S24 34 RD (unique items)
S25 1267 S10 NOT (S0 OR S16 OR S20 OR S23 OR LENS OR LENSES OR PHOTOMASK? OR
LITHOGRAPH? OR MICROLITHOGRAPH?)
S26 1110 S25/ENG OR (S25 AND LA=ENGLISH)
S27 1010 RD (unique items)
S28 636 S27 NOT (BREAST? ? OR MAMMAR? OR HYDROXYAPATITE OR DELIVERY OR SPINE
OR VERTEBRA? OR DISC? ? OR CORNEA? ?)
S29 367 S28 AND PY=2004:2006
S30 367 RD (unique items)

FILTRATION SEARCH STRATEGY

b 411; sf allscience not patents

Your last SELECT statement was:
S (CATOX OR (NON()SORBENT()BASED()ADSORPTION) OR (("TIC/TIM" OR (TIC()TIM) OR TICTIM)()REMOVAL) OR (MICRO()REACTOR? ?) OR MICROREACTOR? ? OR (PHOTOCATALYTIC ()OXIDATION) OR (CATALYTIC()REACTOR? ?)) AND (FILTER? ? OR FILTATION OR MASK? ?)

SYSTEM:OS - DIALOG OneSearch
File 155:MEDLINE(R) 1951-2006/Jun 12 (c) format only 2006 Dialog
File 6:NTIS 1964-2006/Jun W1 (c) 2006 NTIS, Intl Cpyrght All Rights Res
File 103:Energy SciTec 1974-2006/Apr B2 (c) 2006 Contains copyrighted material

File 2:INSPEC 1898-2006/Jun W1 (c) 2006 Institution of Electrical Engineers
File 73:EMBASE 1974-2006/Jun 13 (c) 2006 Elsevier Science B.V.
File 16:Gale Group PROMT(R) 1990-2006/Jun 12 (c) 2006 The Gale Group
File 315:ChemEng & Biotec Abs 1970-2006/May (c) 2006 DECHEMA
File 8:Ei Compendex(R) 1970-2006/Jun W1 (c) 2006 Elsevier Eng. Info. Inc.
File 148:Gale Group Trade & Industry DB 1976-2006/Jun 12 (c)2006 The Gale Group
File 144:Pascal 1973-2006/May W3 (c) 2006 INIST/CNRS
File 354:Ei EnCompassLit(TM) 1965-2006/Jun W2 (c) 2006 Elsevier Eng. Info. Inc.
File 34:SciSearch(R) Cited Ref Sci 1990-2006/Jun W1 (c) 2006 Inst for Sci Info
File 399:CA SEARCH(R) 1967-2006/UD=14425 (c) 2006 American Chemical Society

Set Items Description
S1 36 CATOX
S2 0 (NON()SORBENT()BASED()ADSORPTION)
S3 0 (("TIC/TIM" OR (TIC()TIM) OR TICTIM)()REMOVAL)
S4 12023 (MICRO()REACTOR? ?) OR MICROREACTOR? ?
S5 5158 (PHOTOCATALYTIC()OXIDATION)
S6 12990 (CATALYTIC()REACTOR? ?)
S7 26533 CATALYTIC()OXIDATION
S8 1053699 FILTER? ? OR FILRATION
S9 228140 MASK? ?
S10 1262126 RESPIRATOR? ?
S11 1 ((NON()SORBENT) OR NONSORBENT)(5N)ADSORPTION
S12 463845 FILTRATION
S13 1053 (S1 OR S4:S7 OR S11) AND (S8:S10 OR S12)
S14 466832 PORTABLE OR PORTABILITY
S15 602 MANPORTABLE
S16 119895 SOLDIER? ? OR WARRIOR? ? OR WARFIGHTER? OR (WAR()FIGHTER? ?)
S17 34392 BATTLEFIELD
S18 44 S13 AND (S14:S17)
S19 35 RD (unique items)S20 503 (S13 NOT S18) AND PY=2000:2006
S21 457 S20/ENG OR (S20 AND LA=ENGLISH)
S22 282 RD (unique items)

COOLING SEARCH STRATEGY

b 411; sf allscience not patents

Your last SELECT statement was:
S (MASK? ? OR FACEPIECE? OR RESPIRATOR? ?) AND (((MINI OR MICRO OR MINIATURE)()(FAN OR FANS OR BLOWER? ? OR COOLER? ? OR PAPR OR (HEAT()PUMP??))) OR THERMOELECTRIC? OR (MEMS()COOLING) OR (THIN()FILM()SUPERLATTICE))

SYSTEM:OS - DIALOG OneSearch
File 155:MEDLINE(R) 1951-2006/Jun 14 (c) format only 2006 Dialog
File 6:NTIS 1964-2006/Jun W1 (c) 2006 NTIS, Intl Cpyrght All Rights Res
File 103:Energy SciTec 1974-2006/Apr B2 (c) 2006 Contains copyrighted material
File 266:FEDRIP 2005/Dec Comp & dist by NTIS, Intl Copyright All Rights Res
File 198:Health Devices Alerts(R) 1977-2006/May W1 (c) 2006 ECRI-nonprft agncy
File 104:AeroBase 1999-2006/Mar (c) 2006 Contains copyrighted material
File 317:Chemical Safety NewsBase 1981-2006/Jun (c) 2006 Royal Soc Chemistry
File 73:EMBASE 1974-2006/Jun 15 (c) 2006 Elsevier Science B.V.
File 8:Ei Compendex(R) 1970-2006/Jun W1 (c) 2006 Elsevier Eng. Info. Inc.
File 2:INSPEC 1898-2006/Jun W1 (c) 2006 Institution of Electrical Engineers
File 144:Pascal 1973-2006/May W3 (c) 2006 INIST/CNRS
File 399:CA SEARCH(R) 1967-2006/UD=14425 (c) 2006 American Chemical Society

Set	Items	Description
S1	147155	MASK? ?
S2	604	FACEPIECE?
S3	1044982	RESPIRATOR? ?
S4	201	((MINI OR MICRO OR MINIATURE)()(FAN OR FANS OR BLOWER? ? OR COOLER? ? OR PAPR OR (HEAT()PUMP??)))
S5	93817	THERMOELECTRIC?
S6	3	(MEMS()COOLING)
S7	107	(FACE()PIECE?)
S8	117	(THIN()FILM()SUPERLATTICE)
S9	107	(S1:S3 OR S7) AND (S4:S6 OR S8)
S10	85	S9/ENG OR (S9 AND LA=ENGLISH)
S11	63	RD (unique items)
S12	470	(S1:S3 OR S7)(5N)(COOL OR COOLING OR DEFOG?)
S13	14	S12 AND (FAN OR FANS OR BLOWER? ? OR COOLER? ? OR PAPR OR (HEAT()PUMP??))
S14	10	RD (unique items)

APPENDIX B

PATENTS RELEVANT TO RESPIRATOR FACIAL SEAL

Table B-1. Summary of Patents Relevant to Respirator Facial Seal

Patent No.	Company	Seal Technology
7017577	Baxter	The periphery includes a seal that surrounds the nostrils and the mouth and that sticks to the skin of the face. The adhesive of the seal may be a skin friendly adhesive or a skin unfriendly adhesive. With the skin unfriendly adhesive, the adhesive has a strength sufficient to remove a first layer of skin from the face when the seal is pulled from the face.
7013891	DSTL	A respirator comprises an inner, oronasal, mask enclosed within an outer, face-sealing, mask so as to define a cavity; air is inhaled and exhaled solely through the inner, oronasal mask and so substantially no air pressure differential exists between the ambient atmosphere and said cavity which will allow ambient air to enter said cavity
7007690	U.S. Army	Hybrid in-turned seal hybrid intern and flat seal approach. The face seal is flat, i.e. a feathered edge, at the part of the mask that seals against the forehead, but is an inwardly curved seal on the remainder of the mask.
6957653	CDC	Dual seal compartment that is flushed with exhaled air (i.e., clean air obtained by passage through a filtering element or elements). Exhaled air is passed from the breathing space into a flushing channel formed between the primary and secondary seals.
6775850	Morning Pride	In a protective combination wearable by a firefighter or by an emergency worker, when inflated so as to press the tubular hem along the peripheral edge of the hood into the outwardly opening trough, whereby to provide a seal between the face mask and the hood.
6418928	Mallinckrodt	An inner plenum with a gas inlet and a manifold adapted to fit under the nose of a wearer, a pair of nasal inserts projecting from the manifold to define primary seals with the nasal passages of the wearer, an outer plenum adapted to surround at least the nose of the wearer, a secondary seal mounted on an outer edge of the outer plenum and adapted to contact the face of the wearer around the nose in air tight relation, and at least one opening formed in the inner plenum to permit gas to flow into the outer plenum. By pressurizing the outer plenum, the mask decreases the pressure differential between the interior of the mask and the outside atmosphere to reduce the gas flow rate out of the mask in the event of a leak. Diversion of gas into the outer plenum also allows use of an inflatable secondary seal to maintain air-tight contact with the face of the user.
5649532		Inflatable bellows for aircrew mask to press the periphery of the face-piece towards the pilot's face
57338094		Inflatable cuff on anesthesia mask
6152137		Gel seal A sealing pad (14) made of a compliant and resiliently deformable gelatinous elastomer suitable to conform under pressure to form a substantially airtight seal with at least a portion of the user's skin adjacent to the sealing pad (14). The gelatinous elastomer may be attached to a second material by incorporating the gelatinous elastomer into a large plurality of interstitium in the second material. In addition, the second material can be configured to form an endoskeleton or exoskeleton that modifies the physical properties of the gelatinous elastomer.

Table B-1. Summary of Patents Relevant to Respirator Facial Seal (Cont'd)

Patent No.	Company	Seal Technology
5181506	U.S. Army	Gel filled channel A gas mask having a facepiece comprised of three separate transparent layers secured around their peripheries in a detachable manner, the inner layer being made of soft material, the middle layer being made of material that flexibly retains its form, and the outer layer being made of material for protection against liquid agents. An eye outsert is formed from the middle layer over the area around the eyes of a wearer, and a nose cone is formed from the middle layer so as to provide space about the nose and mouth. Inhaled air is drawn through channels formed in the middle layer that extend from the periphery of the facepiece to the outsert. After passing through the outsert, inhaled air passes through a channel formed in the middle layer to the nose cone. A passageway is provided for exhaled air to pass from the nose cone. Prescription lenses for the wearer are integrally formed in a member that can be snapped into the eye outsert. Seals are provided around the periphery of the facepiece and around the nose cone by channels in the middle layers that are filled with a gel and/or compressed air. A hood of treated elastic material fits over the head of the wearer so as to draw the seals into contact with the wearer's skin. The hood surrounds the neck and has a flap that overlies the chest of the wearer, and an air pump and decontamination cannister coupled to the channels for inhaled air are mounted in the flap. Electronic controls are also mounted on the flap for controlling the pump so as to maintain a constant pressure between inhaled and exhaled air.
5540223	Respironics	A flexible, resilient respiratory mask facial seal adapted for confronting engagement with the face of a user to form an annular sealed interface encompassing a predetermined portion of the user's face. The facial seal includes a peripheral wall and an inturned flap seal. The flap seal projects radially inwardly of the peripheral wall and defines a contoured sealing surface adapted for confronting and sealing engagement with the user's face. The flap seal includes a recessed area corresponding substantially in the shape to a human nose for continuously and matingly conforming to the front and side contours of the user's nose when the facial seal is brought into confronting engagement with the user's face. The facial seal may be adapted for attachment to a respiratory mask body or may be removably placeable over the facial seal of an existing respiratory mask.

Table B-1. Summary of Patents Relevant to Respirator Facial Seal (Cont'd)

Patent No.	Company	Seal Technology
6895965	Respironics	A seal and a mask having a seal adapted for confronting engagement with a surface of a user to form an interface therewith. The seal includes a first portion defined by a gel substance and a second portion associated with the first portion. The second portion includes a selectively formable substance adapted to be molded from a first pattern into a second pattern and to retain the second pattern responsive to being so molded. The seal and mask having the seal is tailored to patient by causing the formable portion of the seal to be placed in a malleable state, applying the seal to the patient while the formable portion is in the malleable state, and causing the formable portion to be placed in a fixed state to retain a shape generally conforming to the portion of the patient underlying the seal.
6712072	MAP GmbH	In achieving this object, the invention starts out from the basic idea that at least the edge area of the respirator mask, which can be placed over the nose and/or mouth of a patient, consists of a deformable material which is supported by a supporting structure (supporting frame or supporting element) which is stiff at normal ambient temperatures but can, however, be deformed plastically when the temperature increases. Thus, the shape relevant for fitting the respirator mask to the facial shape of the patient can be changed repeatedly at an increased temperature so that the respirator mask can be fitted to the different facial shapes of the patients.
7044130	Sunrise Medical	A nasal mask for applying pressurized gas to a user's respiratory system. The mask includes an inflatable seal which is at least partially filled with a soft open cell foam. The seal includes a manual pump and a pressure release valve for inflating and deflating the seal. The mask includes a brow bar which is connected through a bridge to the mask body. The bridge can be adjusted to position the brow bar against the user's forehead for supporting an upper portion of the mask. Headgear for attaching the mask to the user is attached to the brow bar and is looped over a prong at a lower portion of the mask for securing the lower portion of the mask to the user. The mask can be easily removed from the patient while leaving the headgear and brow bar attached to the user.

Table B-1. Summary of Patents Relevant to Respirator Facial Seal (Cont'd)

Patent No.	Company	Seal Technology
5243971	University of Sydney	A nasal mask which is suitable for use in a continuous positive airway pressure system. The mask has a face contacting portion mounted to a shell which is sized and shaped to overfit the nose region of an intended wearer, and the face contacting portion is in the form of a distendable membrane which is moulded from an elastic plastics material. The distendable membrane and the shell together define a chamber, and pressurized gas admitted to the chamber causes the membrane to distend outwardly from the shell. When placed in contact with the face of the wearer, the distendable membrane is caused to overlay the covered facial regions and, under the influence of the pressurized gas, to conform three-dimensionally with the contours of the overlayed regions. An orifice is formed within the membrane and is shaped and positioned to admit gas from the chamber to the nasal passages of the wearer.
4971051		A face mask having a perimeter for sealing against the face of a user is incorporated in a continuous positive airway pressure mask (CPAP) for treatment of central and obstructive sleep disorders. An elongate flexible pneumatic cushion seal is formed around the perimeter of the mask. An air passageway is coupled to the pneumatic air cushion. An inflatable expandable balloon chamber is coupled in open communication through the air passageway to the elongate pneumatic cushion seal. The balloon chamber is inflated to a desired pressure for passage of air between the pneumatic cushion seal and the expandable balloon chamber at said pressure. The pneumatic cushion seal is maintained against the face of a user and follows the changing contours of a user's face by passage of air between the pneumatic cushion seal and the expandable balloon chamber at the desired pressure. This changing volume of air in the pneumatic cushion seal assures that the seal is maintained. A flap ring of a flexible membrane positioned at the perimeter of the mask extends radially inwardly from the perimeter. The flexible membrane flap ring is formed with a central opening for the user to breathe in the mask. Air flowing into the mask seals the flexible membrane flap ring against the facial contours providing additional sealing for the CPAP mask.
5575278	Intertechnique	The equipment is usable by a person exposed to NBC threats. It has a helmet, a face-cover provided with fastenings for connection to the helmet and with a coupling for a breathing gas feed or ventilation hose. A flexible envelope extends the helmet and the face-cover downwards. For providing sealed connection between the helmet, the face-cover, and the envelope, a hoop is fixed to the helmet in permanent or removable manner. It projects from the base of the helmet forwards. The top edge of the hoop receives the face-cover and the lower edge hoop receives the envelope in sealed manner.

Table B-1. Summary of Patents Relevant to Respirator Facial Seal (Cont'd)

Patent No.	Company	Seal Technology
5836303	Thermal Air Products	Respirator apparatus comprises a mask with a passage and a mesh material disposed across the passage. The mesh material is fused between two layers of the mask material in a molding process. The mask is made of a cross-linked polyethylene material that is flexible, resilient, impervious to liquids, and a good insulator. The cross-linked polyethylene material may be formed to fit the individual facial contours of the wearer, and has a memory. A lip is disposed across the top of the mask, and provides a seal, preventing moist air from escaping that may fog the goggles or the glasses of the wearer.
0023228		3D scan of face followed by custom fit mask
0060196		Dual chamber mask, outer seal and inner seal eyes mouth nose
WO 02/11804	Mallinckrodt	Shell worn over head that mask attaches to
WO 03/095031	Qinetiq Limited	Flexible hood with sealing surface for mask
WO 2005/060374	Safety Tech Int	Pump used to inflate mask seal
WO 2004/066764	Biokidz, Inc	Biohazard mask with gel-filled seal or combination memory/gel filled seal
WO 2004/052439	Emergent Respiratory Products	Foam cuff seal with non-reticulated ester polyurethane foam